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(6) DIRECT DRIVE CONTROL VALVE FOR FLY-BY-WIRE FLIGHT CONTROL SYSTEM ACTUATORS,

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Binghamton, New York

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The development of a high force linear motor suitable for directly actuating an aircraft hydraulic powe r control valve is used on a flight control system actuator is described. A breadboard unit was fabricated and tested and met the 80 lb. midpoint force requirement with an input of 4.4 amperes (1.1 amps/coil) A modified F-4 aileron actuator incorporating the force motor and position LVDT's met the frequency response requirements. Three sets of brassboard

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equipment each consisting of a modified F-4 aileron actuator incorporating a new force motor and position LVDT's and an electronic control box were designed, fabricated and tested. One set was subjected to and satisfactorily completed flightworthiness tests. The remaining are available for flight testing.

FOREWORD

This Technical Report describes effort performed by the General Electric Company's Aerospace Controls and Electrical Systems Department in Binghamton, New York under USAF Contract F33615-76-C-3037. The contract was initiated under Project Number 2403 entitled "Flight Control System Development", Work Unit 24030202. The USAF Project Engineer/Manager is T.D. Lewis (AFFDL/FGL).

This report covers work performed between April 1976 and December 1977.

The principal contributors to this activity at General Electric were J.E. Rinde and R.M. Perry. Other key individuals involved were M.J. Wildrick, C. Ashley, R.G. O'Connor and D. Hogan.

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INTRODUCTION

BACKGROUND

Electronic control of aircraft flight control power actuators is usually accomplished by a servo valve controlled hydraulic driver stage. The driver stage positions the control valve for the output ram, generating sufficient force to overcome friction, flow forces, and any linkage loads appearing at the valve input point.

The complexity of the driver stage was multiplied by the advent of highly redundant systems where the redundancy of the driver was usually made equal to the redundancy of the electronics. The result was a large and costly actuator function involving triplex or quadrex servo valves, shut-off/by-pass valves, position transducers, etc., to drive the power control valve.

OBJECTIVE

The object of this effort was to develop an electric force motor to replace the hydraulic driver stage and to design and fabricate a flight test system utilizing the new force motor. The system produced consists of:

1) An F-4 aileron actuator modified by the addition of the valve driver and ram position transducers.
2) Single failure correcting electronics.

Also necessary for the flight test installation but not included in this effort are the control position transducers and power and reset controls in the cockpit.

Figure 1 is a photograph of one set of flightworthy equipment.

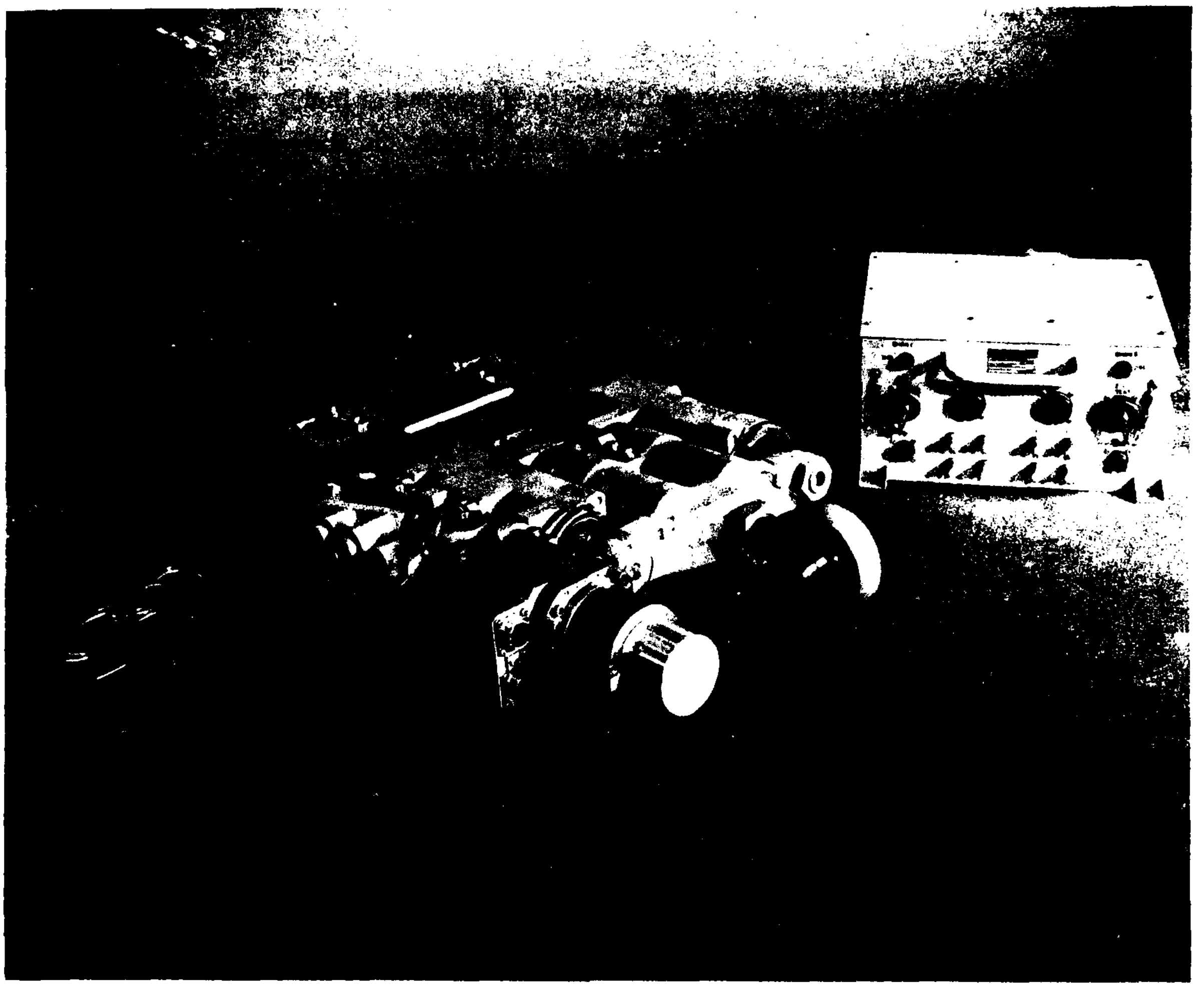


Figure 1. Direct Drive Actuator and Electronics 26203

FORCE MOTOR CONFIGURATIONS

Several tasks directed toward establishing the feasibility of electromechanical valve drivers were accomplished independently prior to this contract.

First, an evaluation of eight approaches was made:

1) Flat Face Plunger Solenoid
2) Plug Plunger Solenoid
3) Conventional Permanent Magnet Torquer
4) Bistable Solenoid
5) Linear Motion Force Motor
6) Linear Permanent Magnet Motor
7) Basic Voice Coil Driver[(1)]
8) Modified Voice Coil Driver [(2)]

The linear motion force motor and the bistable solenoid were ranked equal. The linear motion force motor was selected initially.

The second pre-contract task was the construction and test of a linear motion force motor. Testing revealed that only about one half of the predicted midpoint force and stroke could be achieved. This was caused by a smaller than anticipated air gap flux density due to not accounting for all of the possible leakage permeance paths around the magnets and the relatively large percentage of fringe permeance around the air gaps compared to the useful air gap permeance. Additional analysis and testing have shown that the air gap area, magnet area and the size and weight of linear motion force motor would have to increase significantly in order to meet the design objectives.

---

(1) Multipole, commutated

(2) Coil on moving magnetic structure

Before starting a redesign of the linear motion force motor, the bistable solenoid mechanization was reviewed. This cylindrical configuration used four permanent magnets between the outer iron shell and iron pole piece surrounding the armature to produce the desired permanent magnet flux in the radial air gap and axial air gaps.

The last task carried out prior to the award of this contract was a redesign of the bistable solenoid.

The first iteration design analysis of this configuration revealed that using four magnets resulted in a large amount of leakage around the permanent magnets and from the iron pole to the shell resulting in increased magnet length for a given diameter to obtain the desired air gap flux density. It was obvious that a new permanent magnet arrangement was needed to decrease leakage.

The idea for using a cylindrical magnet arrangement and eliminating the iron pole piece in the bistable solenoid design evolved which led to the bi-directional force motor design.

The bi-directional force motor design has some significant advantages over the linear motion force motor design with regard to weight, size, power consumption and efficiency. Thus it was selected for use on the Direct Drive Control Valve/Actuator Development Program.

FLIGHT TEST APPLICATION

The aileron actuator in the F-4 was selected at the outset of this effort for the flight test installation. A modified actuator will be installed in one wing; the other wing will remain in its original configuration.

The F-4 aileron actuator control valve is typical in terms of its stroke, and force, friction parameters to many aircraft power actuators.

Using the F-4 as the test bed simplifies the installation; i.e., no hydraulic line changes are necessary; only disconnecting the mechanical input and routing the two signal cables. Other details of the installation are identical to the production aircraft procedures.

SECTION II

BREADBOARD DEVELOPMENT

VALVE DRIVER

REQUIREMENTS

The valve driver force output requirement is 80 pounds along the valve centerline at null position and 40 pounds under the same conditions with one failure.[1]

The valve displacement is required to be $\pm$ 0.040 inches minimum and flow 50 cis minimum.[2]

The displacement was increased to $\pm$ 0.066 inches for this design to accommodate the F-4 aileron power valve. The design force was taken at 80 pounds.

VALVE DRIVER SIZING

A cross section of the breadboard model of the bi-directional force motor is shown in Figure 2.

Design calculations for permeance and flux density with armature centered follow for the motor dimensions given:

$$D_{AO} = 1.185 \text{ inch}$$

$$g = 0.015 \text{ inch}$$

$$D_{IM} = D_{AO} + 2g = 1.215 \text{ inch}$$

(1) SOW paragraph 4.3.4 requirement

(2) SOW paragraph 4.3.6 requirement

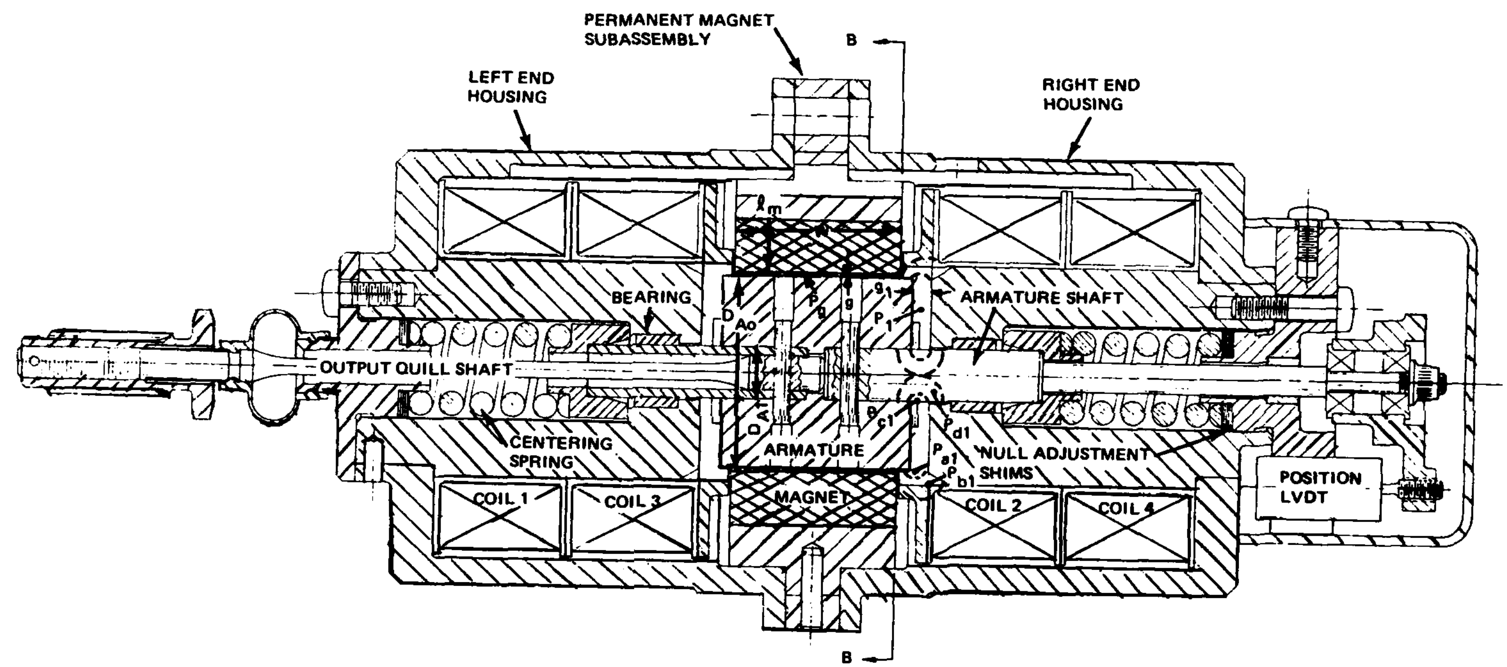


Figure 2. Breadboard Force Motor Configuration

1. Radial Gap Permeance = Pg = Po + Pf

$$Pg = \frac{(D_{AO} + D_{IM})}{2g} \pi W \ (2.54) + \left[(2)\ 0.52\, \pi\ (D_{AO} + g)\right] 2.54$$

$$= \frac{(1.185 + 1.215)}{2(0.015)} \pi (0.99)\ (2.54) + 1.04\, \pi\ (1.20)\ \ 2.54$$

$$Pg = 631.98 + 9.96 = 641.94 \text{ cm}$$

2. Air Gap Permeance = $Pg_1 = Pg_2 = P1 + P_{f1} + P_2 + P_{f2}$

At Centered Armature Position

$$P_1 = \frac{\pi/4 \left[D_{AO}^{\ 2} - D_{A1}^{\ 2} \right](2.54)}{g1} \quad \text{and for} \quad \begin{aligned} D_{AO} &= 1.185 \text{ inch} \\ g1 = g2 &= 0.13 \text{ inch} \\ D_{A1} &= 0.3125 \text{ inch} \end{aligned}$$

$$P_1 = \underline{20.05} \text{ cm}$$

$$P_{fl} = P_{al} + P_{b1} + P_{cl} + P_{dl}$$

$$P_{fl} = 0.26\pi\ (D_{AO} + g\ 1/2)\ (2.54) + 2.54\ D_{AO} \ln\left(1 + \frac{2tbl}{gl}\right)$$

$$+ \ 0.26\pi (D_{Al} - g\ 1/2)\ (2.54) + 2.54\ \ (D_{Al} - \sqrt{gl\ (D_{Al})}\ \ \ell n \left(\frac{D_{Al}}{gl}\right)$$

$$Pfl = 0.26\pi (1.185 - 0.\frac{13}{2})\ (2.54) + 2.54\ \ (1.185)\ \ell n \left[1 + 2\,\frac{(0.07 - 0.015)}{0.13}\right]$$

$$+ \ 0.26\pi\ (0.3.25 - 0.\frac{13}{2})\ \ (2.54) + 2.54\ \ (0.3125 - \sqrt{0.13\ (0.3125)}\ \ell n \left(\frac{0.3125}{0.13}\right)$$

$$P_{gl} = P_1 + P_{fl} = 20.05 + 5.198 = 25.25 \text{ cm}$$

3. Magnet Leakage Permeance = $P\ell$

The leakage permeance of the magnet from one edge of the magnet is bounded by $0.26\ u\ \ell\ P\ell \leq 0.52\ u\ \ell$ where $\ell = \pi D_M = \pi (D_{IM} + \ell m)$ and u = 1 in cgs system of units.

Choosing the worst case for both edges of the smarium cobalt magnet.

$$P_\ell = 2\left[0.52\ \ (D_{IM} + \ell\, m)\ \ 2.54\right] = 1.04\ \ (1.215 + 0.327)\ (2.54)$$

$$P_\ell = \underline{12.79 \text{ cm}}$$

Now the circuit permeance is given by:

$$Pc = \frac{(P_{g1} + P_{g2})\, Pg}{P_{g1} + P_{g2} + P_g} + P\ell = \frac{(50.5)\,(641.94)}{50.5 + 641.94} + 12.79$$

$$Pc = 46.81 + 12.79 = \underline{59.61 \text{ cm}}$$

$$(B/H)_c = Pc \frac{\ell m}{Am} = \frac{59.61\,(0.327)}{\pi(1.542)\,(0.99)\,(2.54)} = 1.600$$

Assuming a minimum B_r of 8300 gauss the magnet flux density is given by:

$$B_m = \frac{Br}{1 + 1/(B/H)_c} = \frac{8300}{1 + 1/1.60} = 5107.7$$

$$\text{Then } \emptyset m = B_m A_m = B_m(\pi D_m W) = 4923\,\pi \quad (1.542 \times 0.99)\,(2.54)^2$$

$$\emptyset m = 158{,}037 \text{ maxwells}$$

$$\text{Now } \emptyset \ell = \frac{B_m \ell_m P\ell}{(B/H)_c} = \frac{4423\,(0.327 \times 2.54)\,(12.79)}{1.60} = 33{,}912 \text{ maxwells}$$

The net flux through the radial gap and armature air gaps is

$$\emptyset g = \emptyset m - \emptyset \ell = 153{,}037 - 33{,}912$$

$$\emptyset g = 124{,}125 \text{ maxwells}$$

At centered armature position where $g_1 = g_2$, $P_{g1} = P_{g2}$

$$\emptyset_{g1} = \left(\frac{P_{g1}}{P_{g1}+P_{g2}}\right) \emptyset g = \frac{\emptyset g}{2} = 62{,}062 \text{ maxwells}$$

The useful flux in the armature air gap is given by:

$$\emptyset_1 = \frac{P1}{Pg1}(\emptyset g1) = \frac{P1}{P1 + P_{f1}}(\emptyset g1) = \frac{20.05}{25.25}(62{,}062) = 49{,}281 \text{ maxwells}$$

$$\text{Then } B1 = \frac{\emptyset 1}{A1} = \frac{49{,}281 \text{ maxwells}}{6.62048 \text{ cm}^2} = 7443 \text{ gauss}$$

Using the Midpoint Force Formula an estimate of the ampere turns necessary to obtain 80 pounds force is given by:

$$NI = \frac{F(g1)\ 4.448 \times 10^5}{0.1\emptyset} = \frac{80(0.13 \times 2.54)\ 4.448 \times 10^5}{0.1\ (49,281)} = 2384 \text{ Amp Turns}$$

The $NI/_{coil}$ for 4 coils is then $\frac{2384}{4} = 596$ Amp Turns

The coil cross section is 0.78 inch x 0.47 inch and using AWG #23 wire with a wire diameter of 0.0241 inch the number of turns that can be accomodated is $N = \frac{(0.78)}{0.0241}\ \frac{(0.45)}{0.0241} = 32 \times 19 =$ 608 Turns. Thus the current in each of the four coils would be about 1.0 amp for an 80 pound midpoint force. The coil resistance would be $R = \pi D_M NRi = \pi (1.84)(608)(0.001696\ \Omega/\text{inch}) = 5.96\,\Omega$ at $20^\circ C$.

From the magnetic circuit calculation, the flux density at centered armature position was computed to be 7440 gauss. To obtain an output midpoint force of 80 pounds, the required ampere turns was 596 per coil for each of four coils. The current per coil is then about 1.0 ampere to produce 80.0 pounds midpoint force or 4.0 amperes total. The computed coil resistance was 5.96 ohms at $20^\circ C$ based on 608 turns per coil.

FORCE MOTOR TESTING

TEST PROCEDURE

A complete breadboard system was fabricated including force motor, electronics, and F-4 aileron actuator.

A test plan for the evaluation of the breadboard system was generated and is included in this report as an Appendix.

TEST RESULTS

TEST RESULTS FOLLOW WHERE PARAGRAPH NUMBERS CORRESPOND TO TEST PROCEDURE PARAGRAPHS OF TEST PLAN INCLUDED AS APPENDIX.

5.1 FORCE MOTOR

5.1.1 FORCE MOTOR CENTERING SPRING FORCE VS POSITION

The centering spring force test was conducted according to the test procedure and the results are shown in Figure 3. This curve presents the net centering spring force with the non-linear star springs removed which is the final configuration used in all of the breadboard tests on the force motor/control valve. In the linear region the net spring gradient is about 345 pound/inch.

5.1.2 FORCE MOTOR POSITION VS CURRENT (POSITION GAIN) AND HYSTERESIS NO EXTERNAL LOAD, OPEN LOOP

The open loop position gain and hysteresis curve shown in Figure 4 was obtained using the test procedure given in Section 5.1.2 of the breadboard test plan. Figure 4 shows that the gain with 4 coils connected is about 0.066 inch/ampere. The gain with 3 and 2 coils connected is essentially identical with no external load applied.

5.1.3 FORCE MOTOR OUTPUT CAPABILITY OVER STROKE, OPEN LOOP

The force motor output capability over the stroke range of 0.067 inch retract to 0.066 inch extend position with four and two coils connected in parallel is shown in Figures 5 and 6. Figure 5 shows that with 4 coils connected the force motor will produce a midpoint (null position) force of 126.5 lb at 9.4 amp total current or 80.0 lb at 4.5 ampere. Figure 6 shows that a midpoint force of 60.0 pounds is achieved at 3.4 ampere with two coils connected in parallel. Figure 5 and 6 show that the force motor has the capability to meet the specified the system design criteria for the electromechanical transducer.

The test circuit shown in Figure 7 was used to measure the force output capability since the single servoamplifier used to measure position gain did not have the required current output capability. The variable voltage, direct current power supply had a current output limit of approximately 10.0 amperes which allowed determination of the force output capability over the force motor stroke. The test circuit also shows the measured room temperature resistance values of the four coils. A schematic of the force motor showing coil location and polarity is also presented in Figure 7.

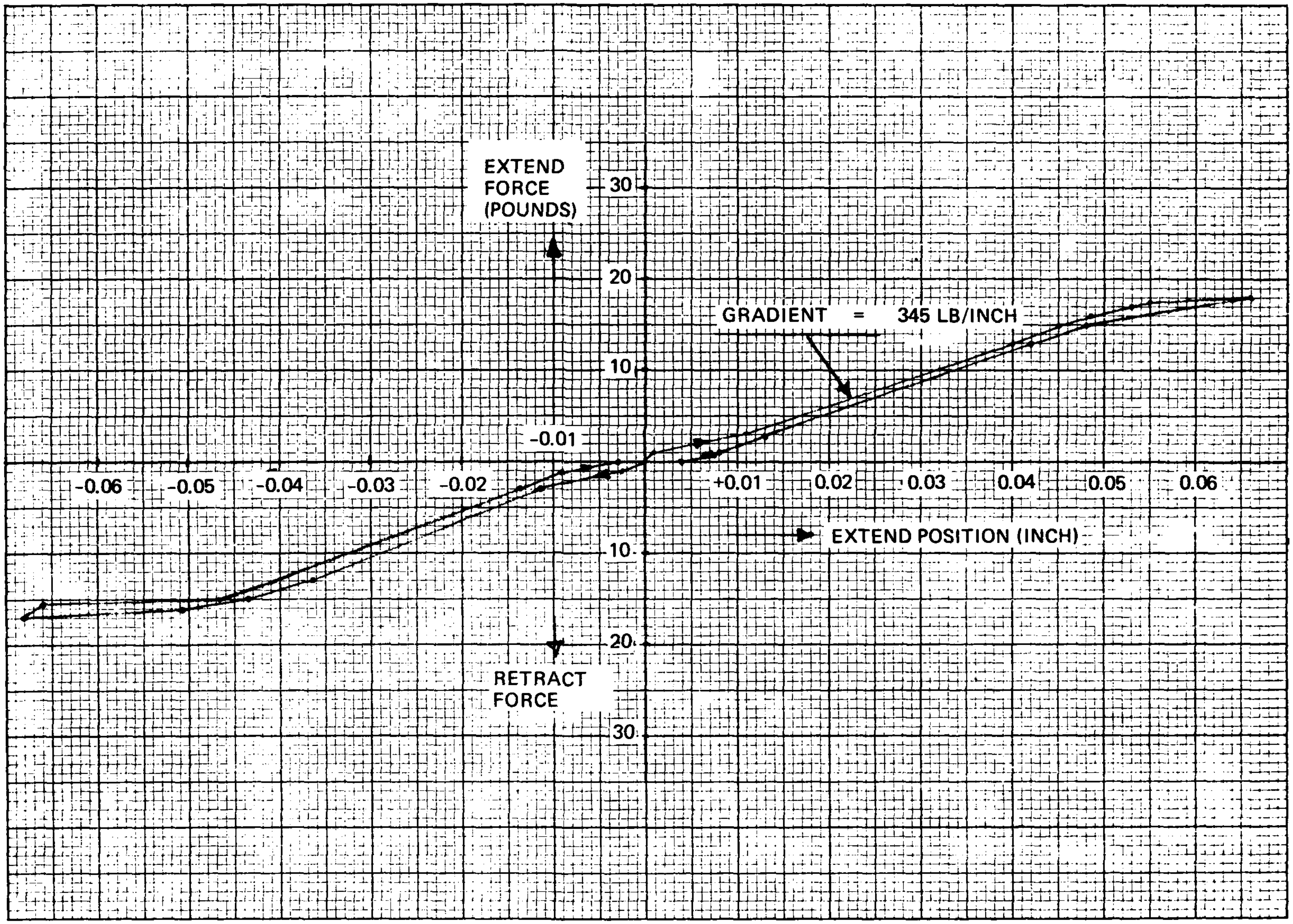


Figure 3. Force Motor Centering Spring Gradient

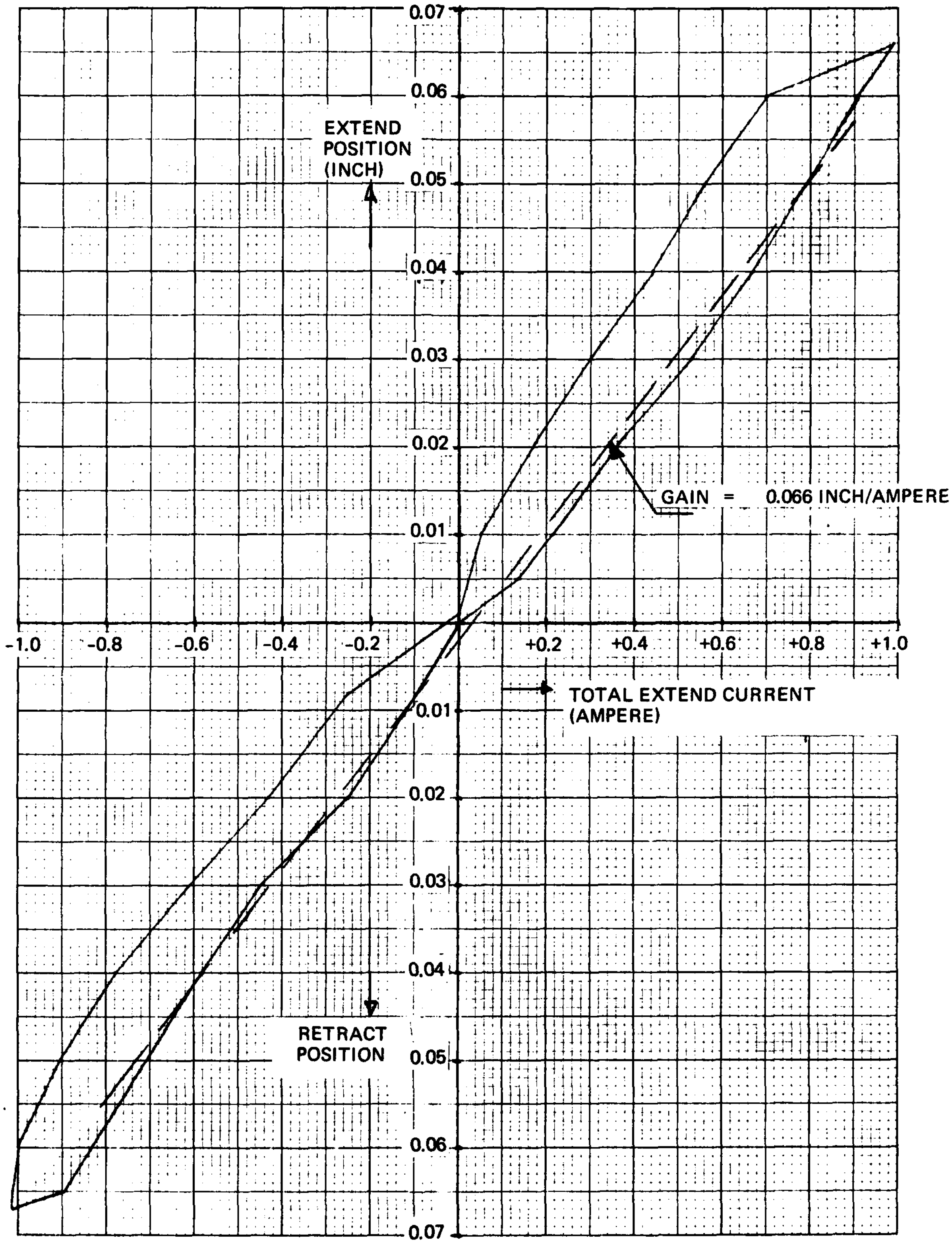


Figure 4. Force Motor Position Gain and Hysteresis, Open Loop Four Coils Connected in Parallel

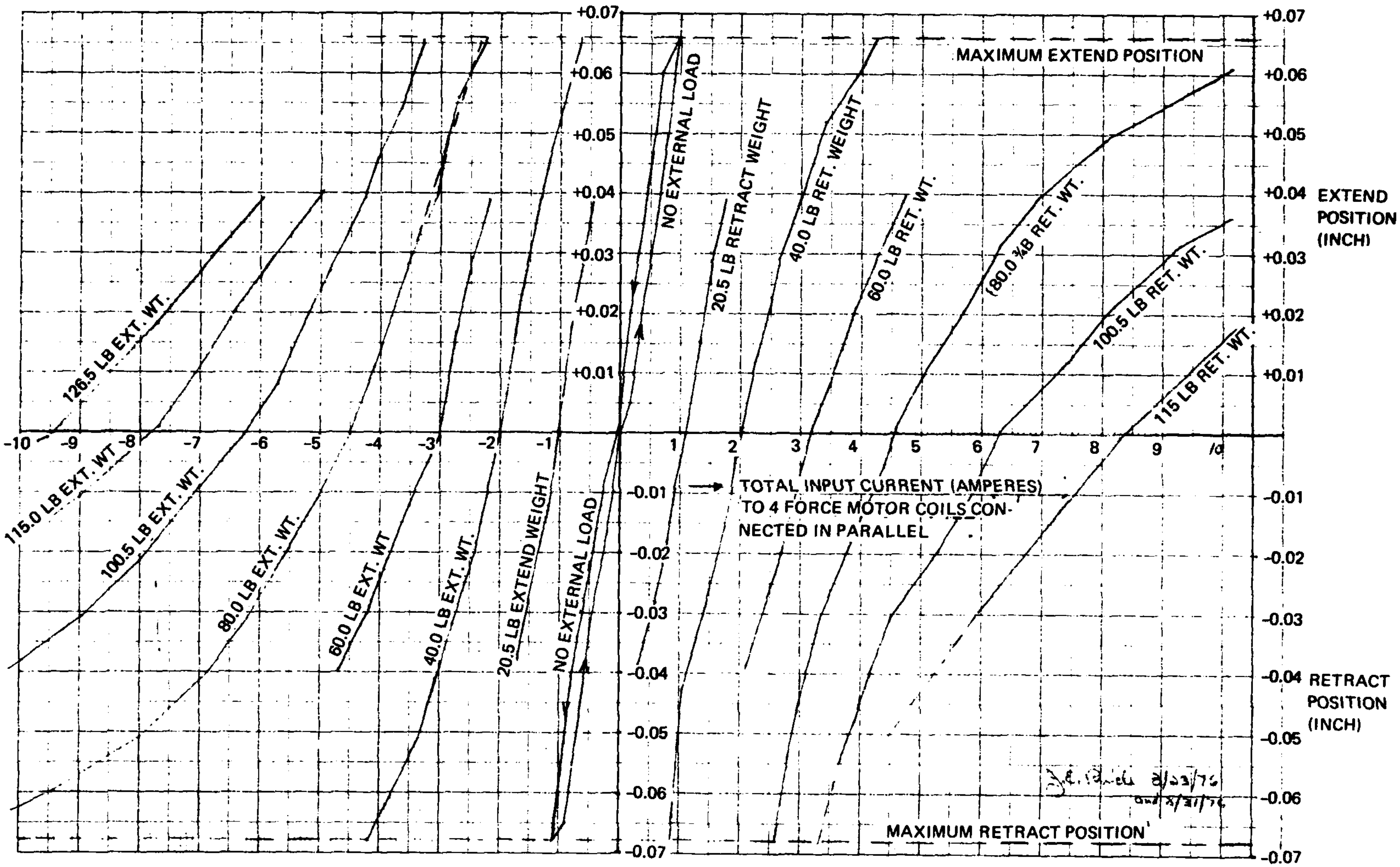


Figure 5. Force Motor Output Capability Over Stroke Limits, Open Loop, Four Coils Connected in Parallel

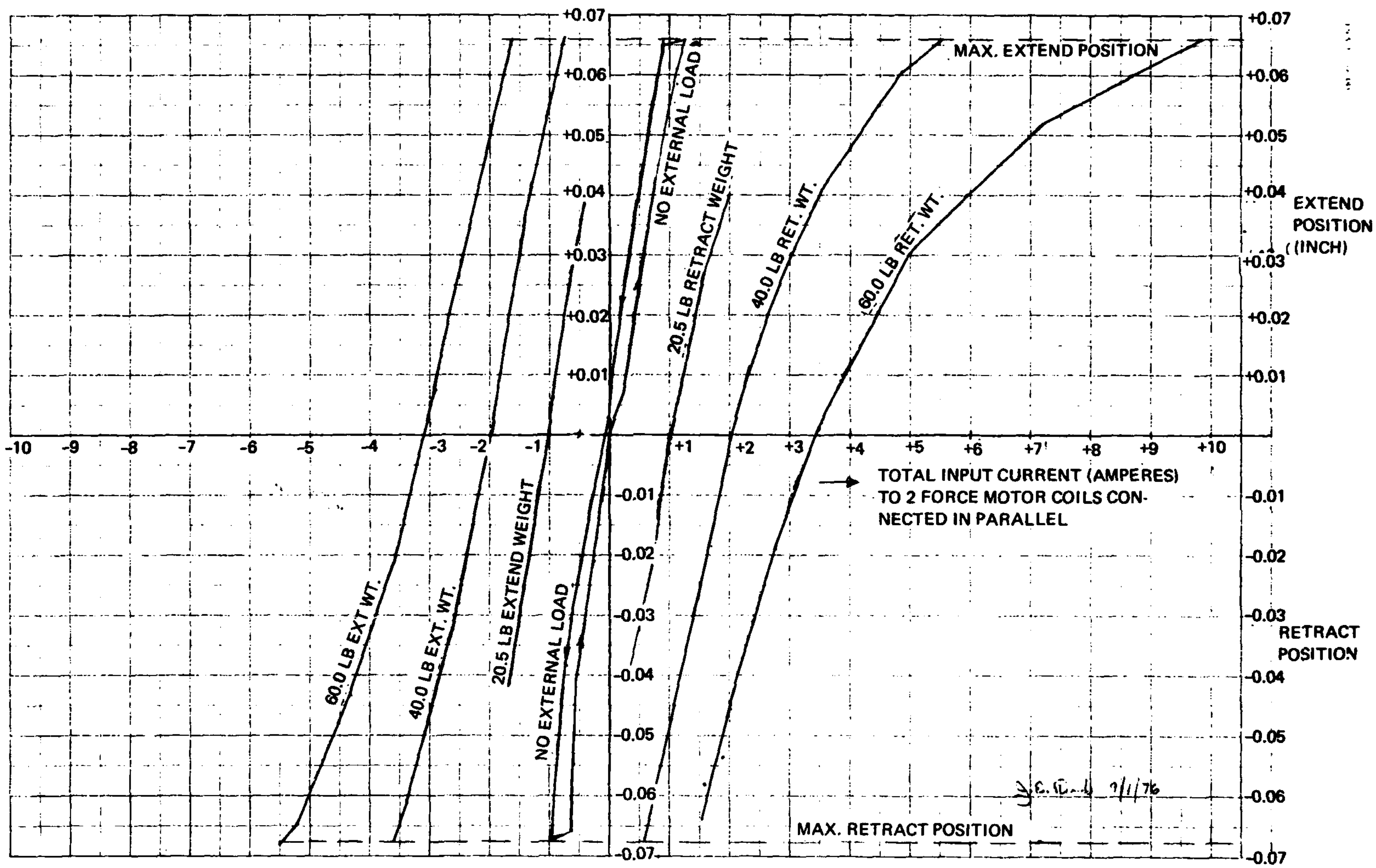


Figure 6. Force Motor Output Capability Over Stroke Limits, Open Loop, Two Coils Connected in Parallel

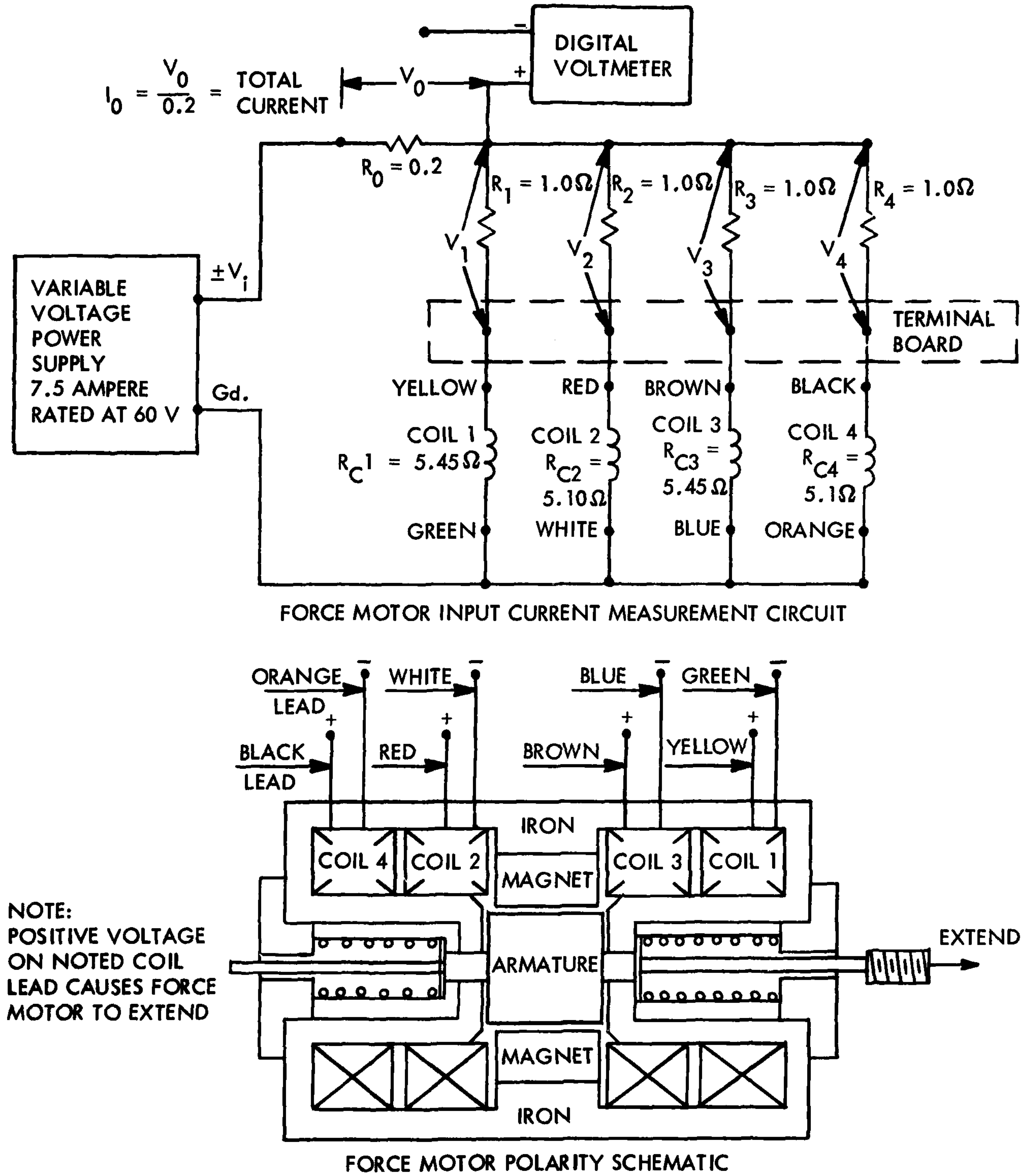


Figure 7. Force Motor Test Circuit and Polarity Schematic

5.1.4 CLOSED LOOP FORCE MOTOR POSITION GAIN

Breadboard tests of the closed loop force motor with a low frequency gain of 112 with four coil and 56 with two coils connected was accomplished. The position gain which is identical for either 4 coil or two coil operation is shown in Figures 8 and 9 .

5.1.5 CLOSED LOOP FORCE MOTOR STIFFNESS

Closed loop stiffness data was taken and the results are shown in Figures 10 and 11 with 4 coils and 2 coils connected. This data was taken with a servoloop dc gain of 112 and 56. Although the force motor servoloop gain was increased at a later date this data is included for completeness.

5.1.6 CLOSED LOOP FORCE MOTOR FREQUENCY RESPONSE AND THRESHOLD TEST

The frequency response shown in Figure 12 at an amplitude of ±0.033 inch at 1.0 Hz reflects the force motor frequency response capability with servoloop dc gains of 112 and 56 for 4 and 2 coils connected. The servoloop gains were changed at a later date and the subsequent change in response is documented in a later section of this report.

TEST CONCLUSIONS

The actual current required to produce 80.0 pounds was found to be about 1.12 amperes/coil or 4.5 amperes total during force motor testing. However, only 550 turns could be wound on the coil cross section area, rather than 608, which required more current. The actual measured resistance was 5.1 to 5.4 ohms for 550 turns/coil.

The power dissipated in the force motor to produce 80 pounds at center stroke is 26.3 watts.

CONTROL VALVE TESTS

TEST PROCEDURE

The F-4 aileron actuator control valve was tested in accordance with the test plan included in this report as an Appendix.

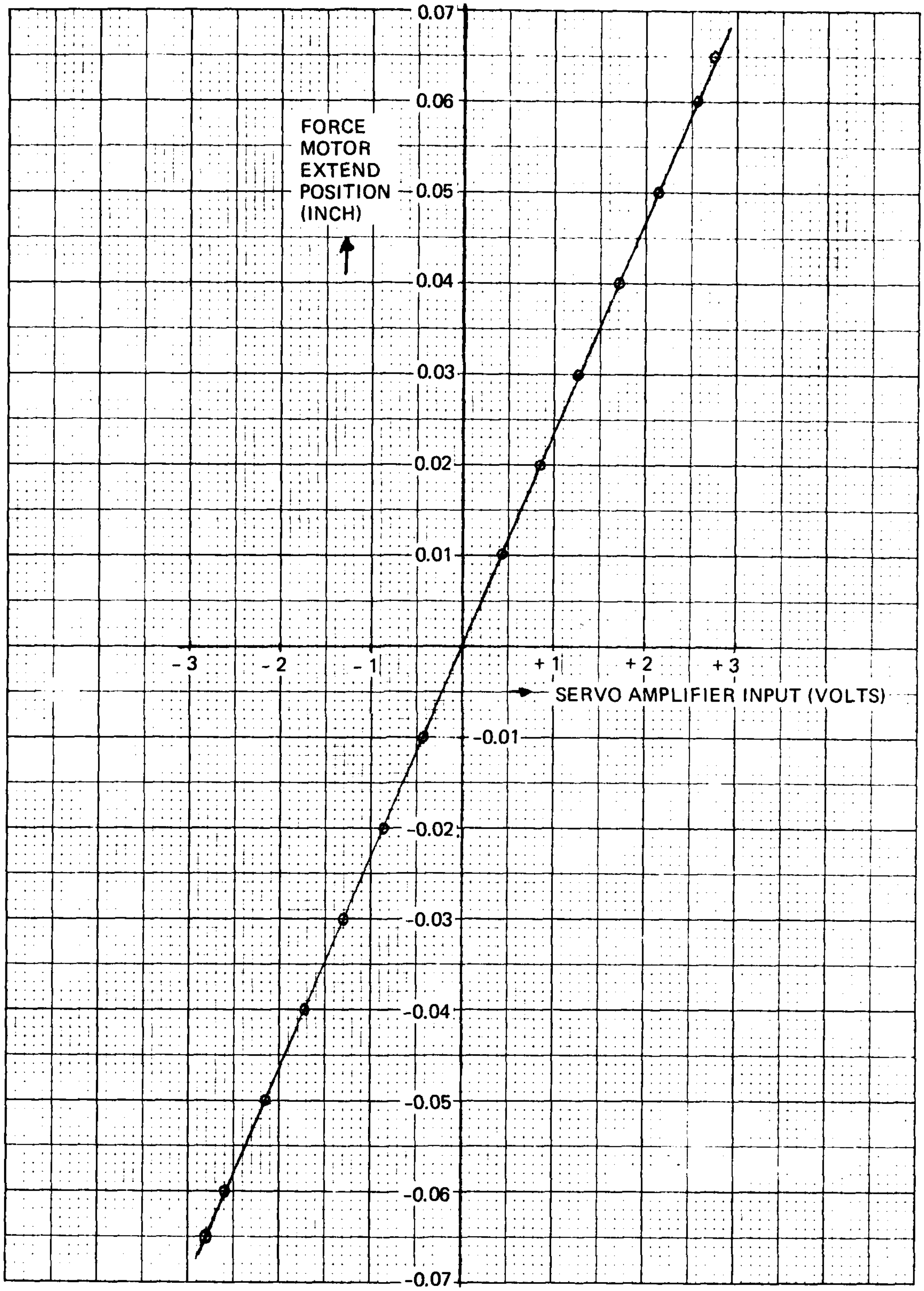


Figure 8. Force Motor Closed Loop Position Gain

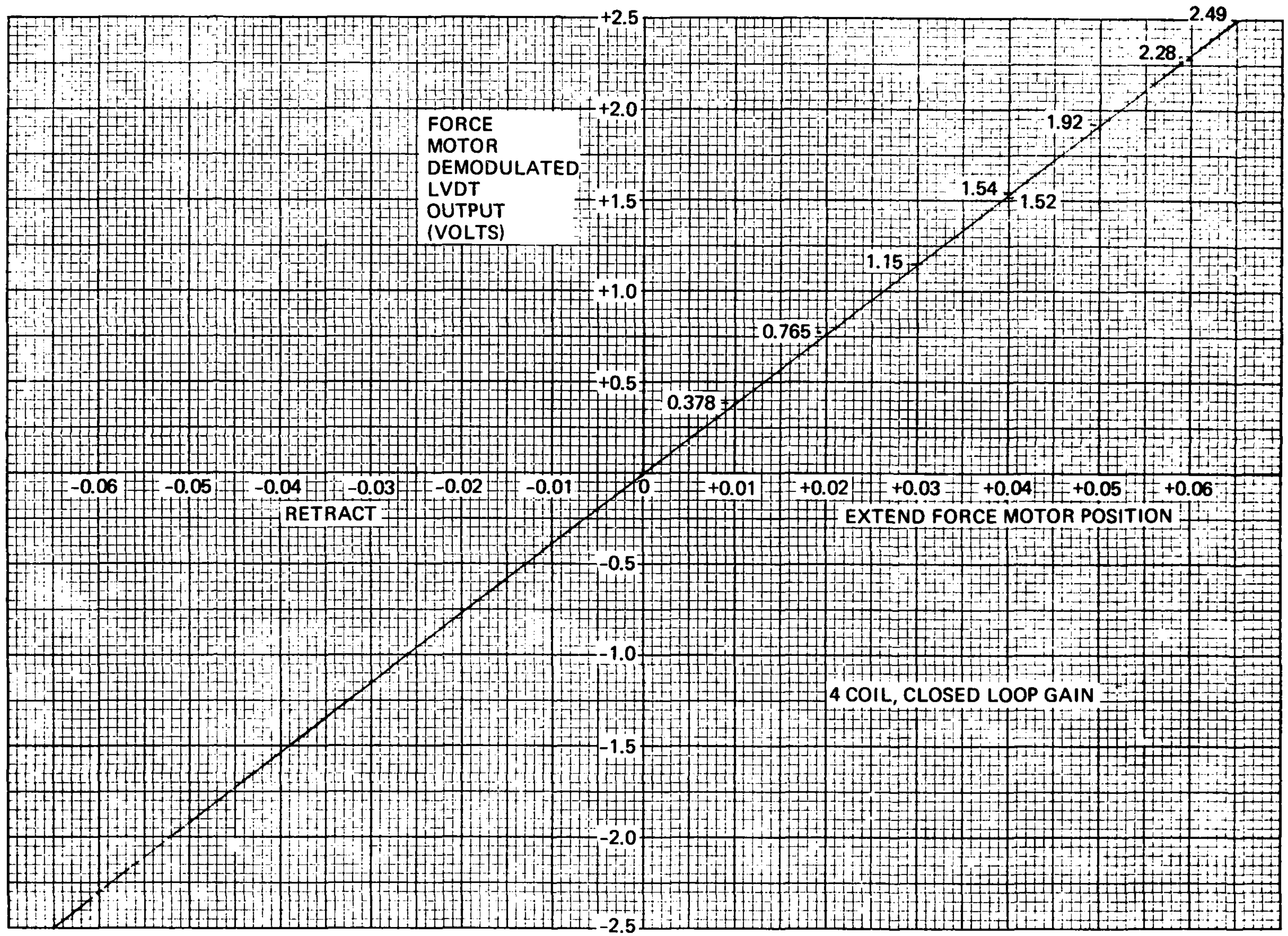


Figure 9. Position Gain of Output Stroke to Output Volts

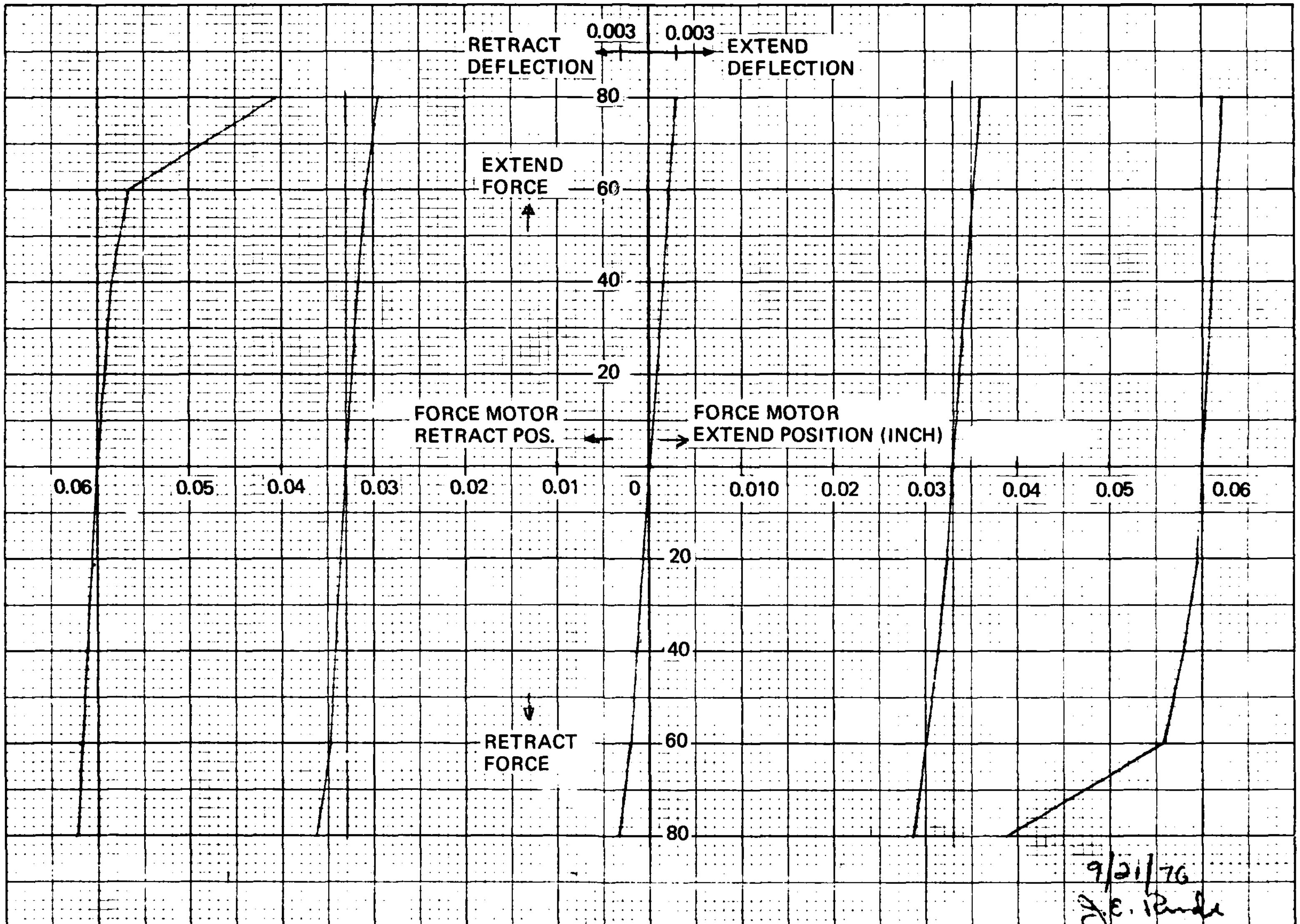


Figure 10. Closed Loop Force Motor Stiffness, Four Coil

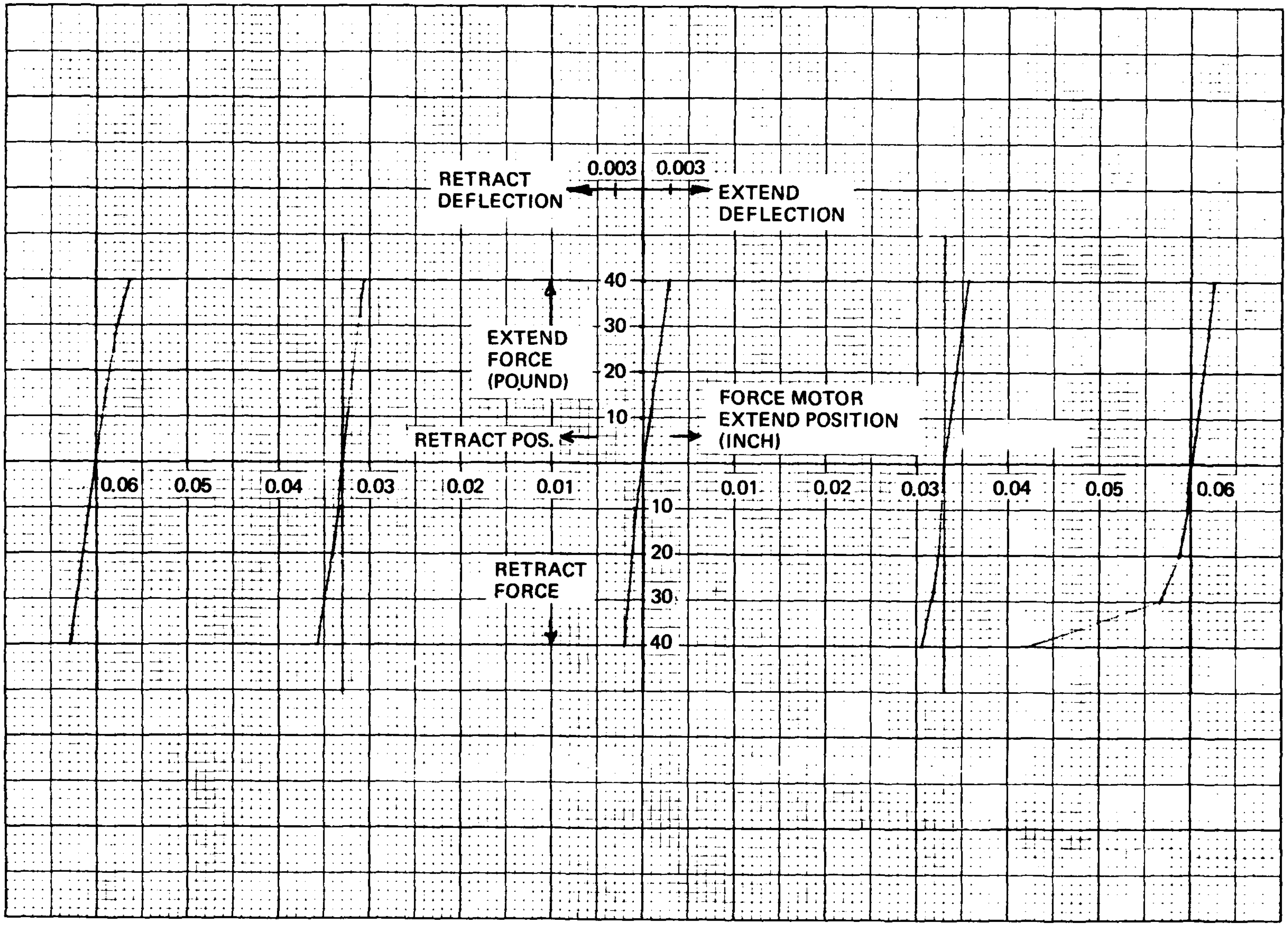


Figure 11. Closed Loop Stiffness, Two Coil

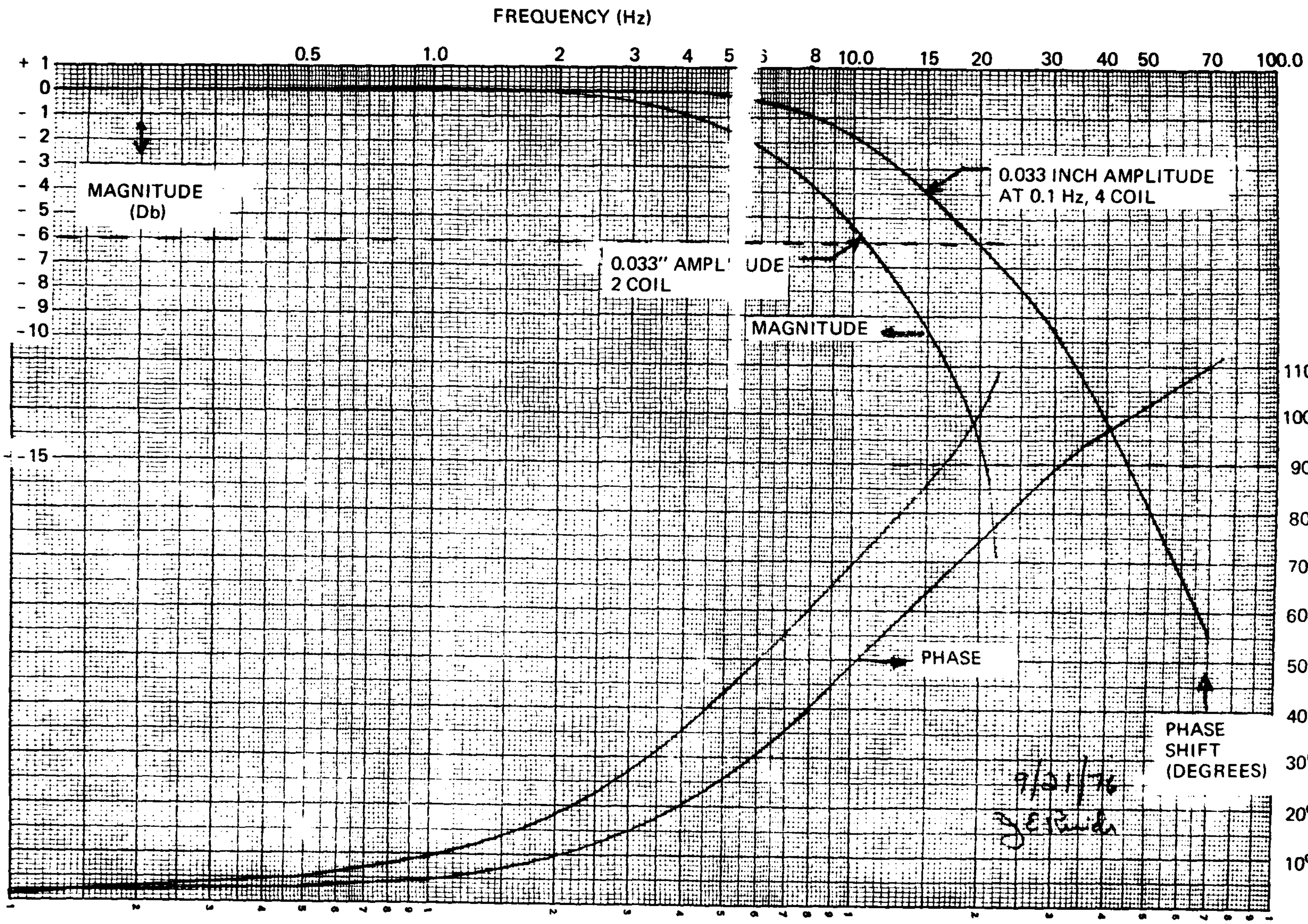


Figure 12. Frequency Response, Four Coil and Two Coil at 50 Percent of Full Stroke

TEST RESULTS

TEST RESULTS FOLLOW WHERE PARAGRAPH NUMBERS CORRESPOND TO TEST PROCEDURE PARAGRAPHS OF TEST PLAN INCLUDED AS APPENDIX.

5.2 F-4 AILERON ACTUATOR CONTROL VALVE TESTS

The initial tests for valve friction, control valve flow and flow reaction force for a single low floworifice, a singlehigh flow orifice and two variable orifices in series as called for in Sections 5.2.1, 5.2.2, 5.2.3 amd 5.2.4 of the breadboard test plan were not conducted. These tests do not represent the normal operating conditions that occur during actuator operation, hence the set tests were deleted.

5.2.5 FLOW AND VALVE REACTION FORCE MEASUREMENT WITH 1000 PSI AND 2000 PSI ACROSS TWO SETS OF TWO VARIABLES ORIFICES IN SERIES

The conditions of this test reflect the normal operating condition of the F-4 aileron, dual tandem control valve and the test results shown in Figure 13 presented the expected friction, valve flow and valve reaction force that the force motor must overcome in actual operation.

These tests were conducted with plastic cap strips installed over the O-ring, return pressure seal on the spool valve. As will be disucssed later in coverage of breadboard electronic testing these cap strips were removed to obtain a lower friction force than the 3.0 to 3.5 pounds shown in Figure 13 as evidenced by a decrease in magneitude of the initial limit cycle oscillation upon removel of the cap strips.

As shown in Figure 13, the valve reaction force is always positive at 1000 psi such that the reaction force will return the valve spool towards neutral. At 2000 psi across the valve the reaction force becomes negative (unstable) above 0.05 inch spool displacement so that the valve will go hardover to the 0.075 inch position where the reaction force is again positive. Without the use of closed loop position feedback on the force motor/ control position, this unstable valve characteristic could lead to erratic or unstable closed loop power actuator operation depending upon the centering spring stiffness of the force motor.

FORCE MOTOR/CONTROL VALVE/ACTUATOR TESTS

TEST PROCEDURE

The force motor/control valve/actuator assembly were tested in accordance with the test plan included in this report as an Appendix.

TEST RESULTS

TEST RESULTS FOLLOW WHERE PARAGRAPH NUMBERS CORRESPOND TO TEST PROCEDURE PARAGRAPHS OF TEST PLAN INCLUDED AS APPENDIX.

5.3 FORCE MOTOR/CONTROL VALVE/ACTUATOR ASSEMBLY

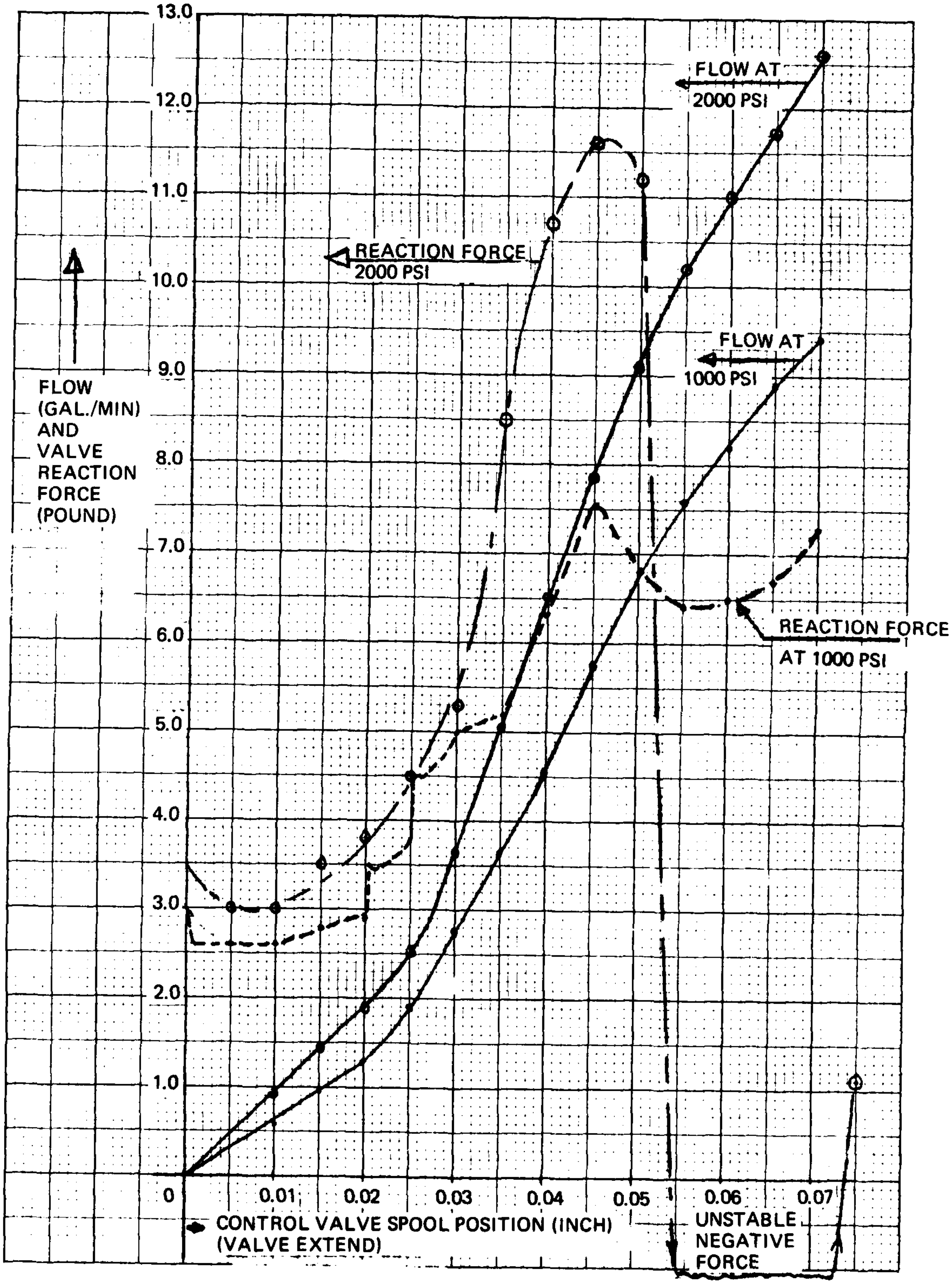


Figure 13. Control Valve Flow and Valve Reaction Force vs Spool Position Per Test Procedure 5.2.5

5.3.1 CLOSED LOOP FORCE MOTOR/CONTROL VALVE POSITION VS INPUT VOLTS, NO FLOW

Figure 14 and 15 present the closed loop position gain of the force motor/control valve as installed in the F-4 Aileron Actuator. The position gain is identical with either four or two coils connected. Figure 16 presents a chart record of the input command, output position and the current to two coils of the force motor as position gain measurements were made. With a single self monitored LVDT feedback to the two control circuits in a channel it can be seen that the current is proportional to the force motor position because of the centering spring. For the high dc gain of 685 used in the two coil servoloop case with cross connection of the error command to the dual servoamplifiers in a control channel, the two currents are forced to track one another.

Figure 17 presents a chart record of the input, output and the four force motor currents when position gain measurements were made with all four coils connected to the servoelectronics. From the chart recording it can be seen that the currents (V_1 and V_2) in channel one are opposing the currents (V_3 and V_4) in channel two as the force motor position is varied from null through an extend-retract cycle. The current fight (equivalent force fight) occurs due to the difference in outputs of the two position LVDTs (mis-track) over the force motor valve stroke. With the high dc servoloop gain of about 460 when all four coils are connected, both channels operating, that was found to be required for minimum residual limit cycle amplitude with the power actuator loop closed, it is difficult to effect a reduction in this current fight. Subsequent testing of the closed loop power actuator has shown that this level of current fight does not appear to have any effect on closed loop power actuator operation where the control valve is at neutral most of the time. As discussed previously, the Active/On-line control concept can be used to reduce current fight.

5.3.2 CLOSED LOOP FORCE MOTOR/CONTROL VALVE POSITION AND FLOW MEASUREMENT WITH 1000 PSI AND 2000 PSI ACROSS TWO SETS OF CONTROL ORIFICES IN SERIES

The curves in Figure 18 present the flow output of one section of the tandem spool valve of the F-4 aileron actuator as a function of spool position at 1000 and 2000 psi differential pressure between supply and return system pressures. Now, the F-4 aileron actuator has a dual tandem, single spool valve that can provide almost the required flow of 50.0 cis with only 2000 psi across the valve as shown in Figure 18. The valve stroke is ±0.066 inch to achieve the desired flow and actuator output velocity. Combining the standard F-4 control valve with the bi-directional force motor that directly drives the valve spool; a control valve module which meets the requirements has been obtained.

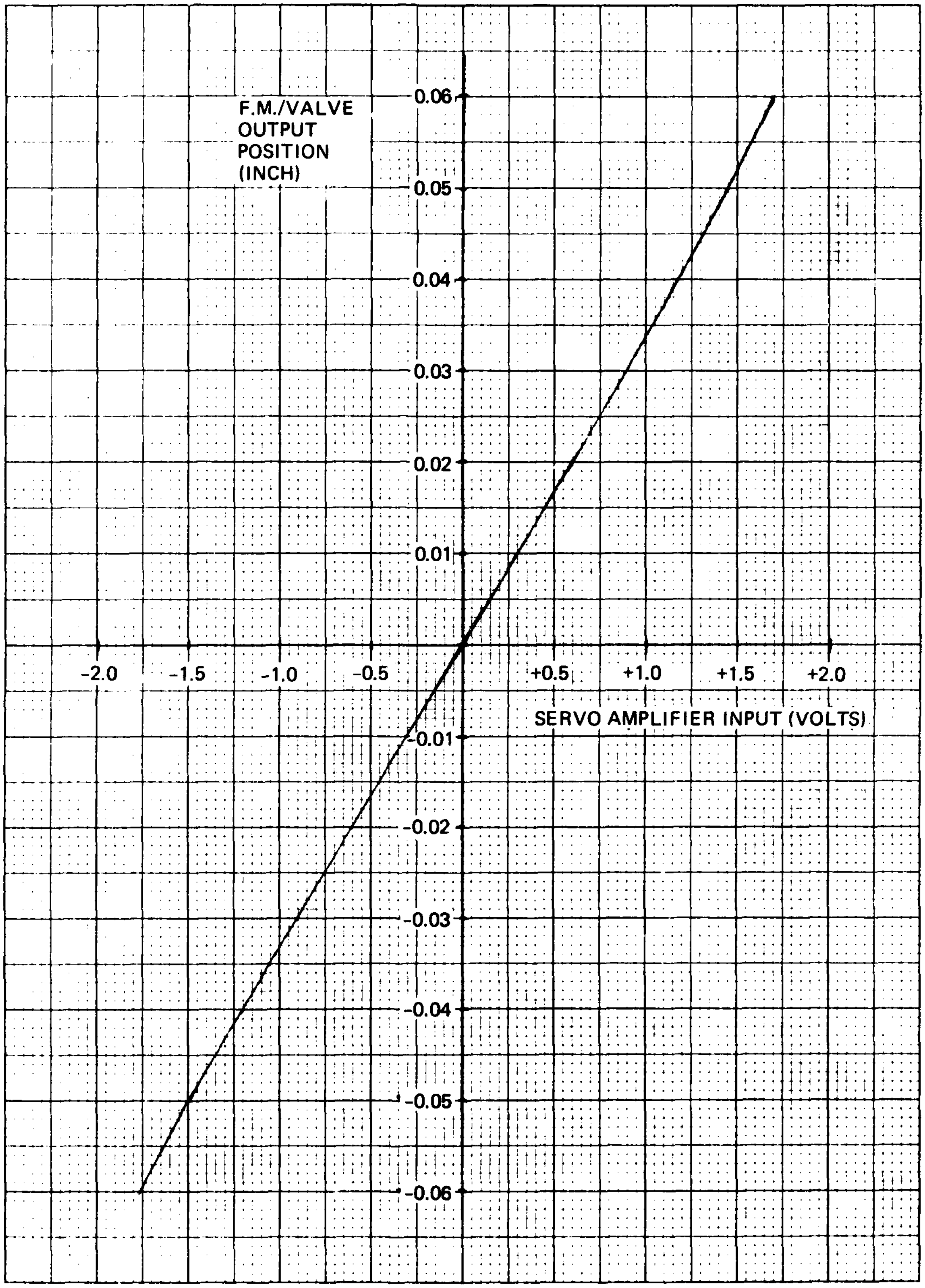


Figure 14. Closed Loop Force Motor Position Gain, No Flow

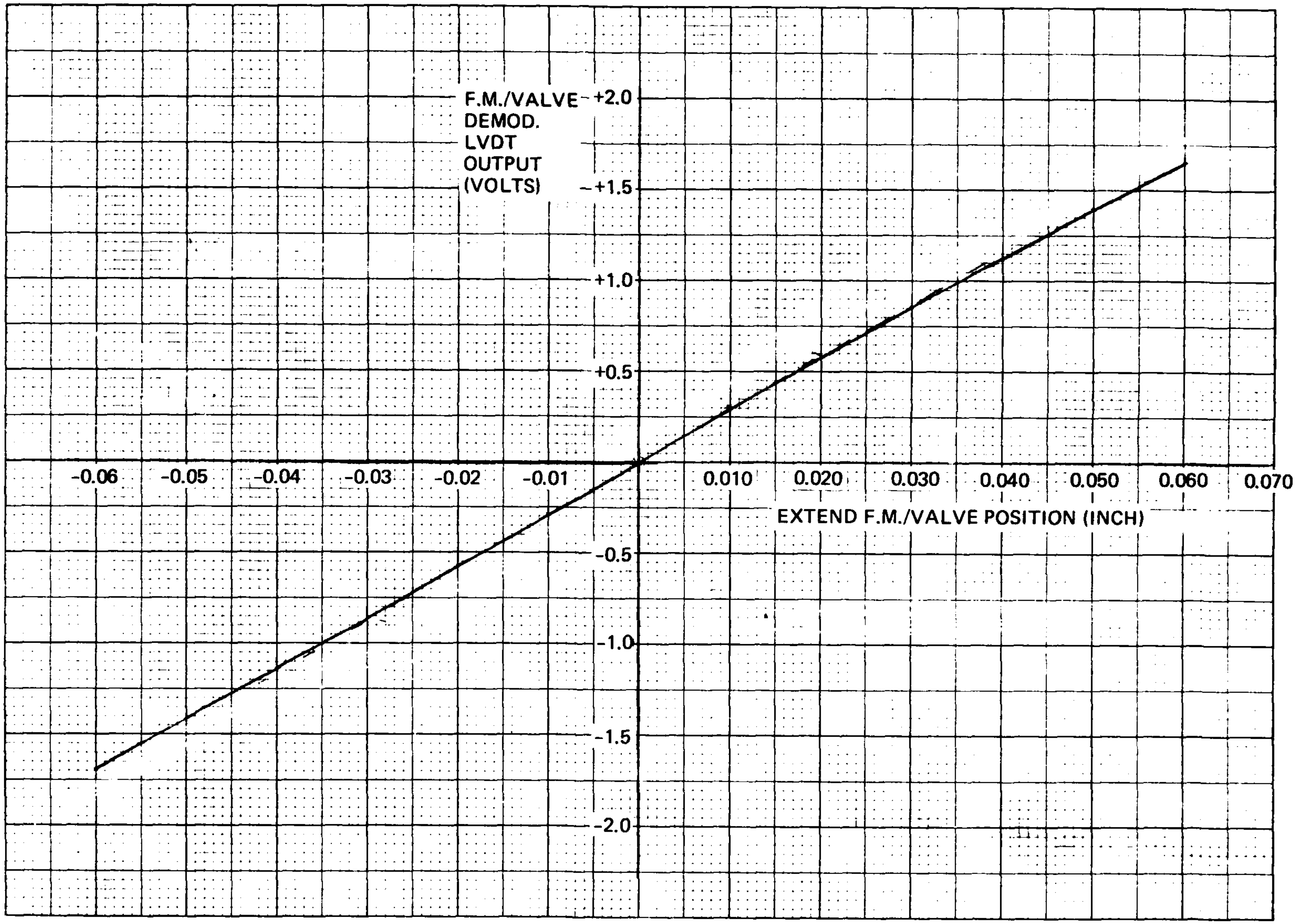


Figure 15. Position Gain of Output Stroke to Output Volts, No Flow

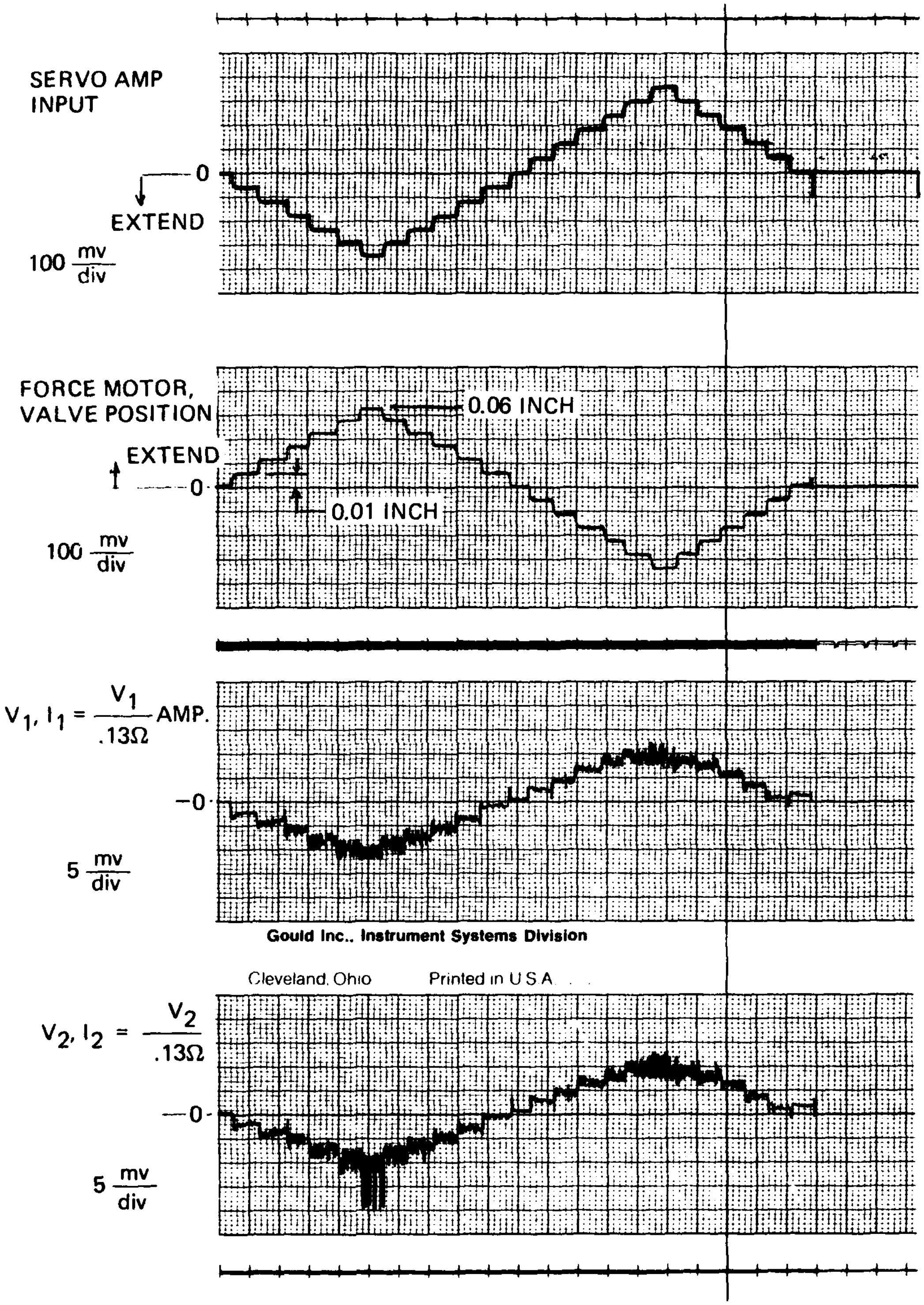


Figure 16. Single Channel, Two Coil Position Gain Recording

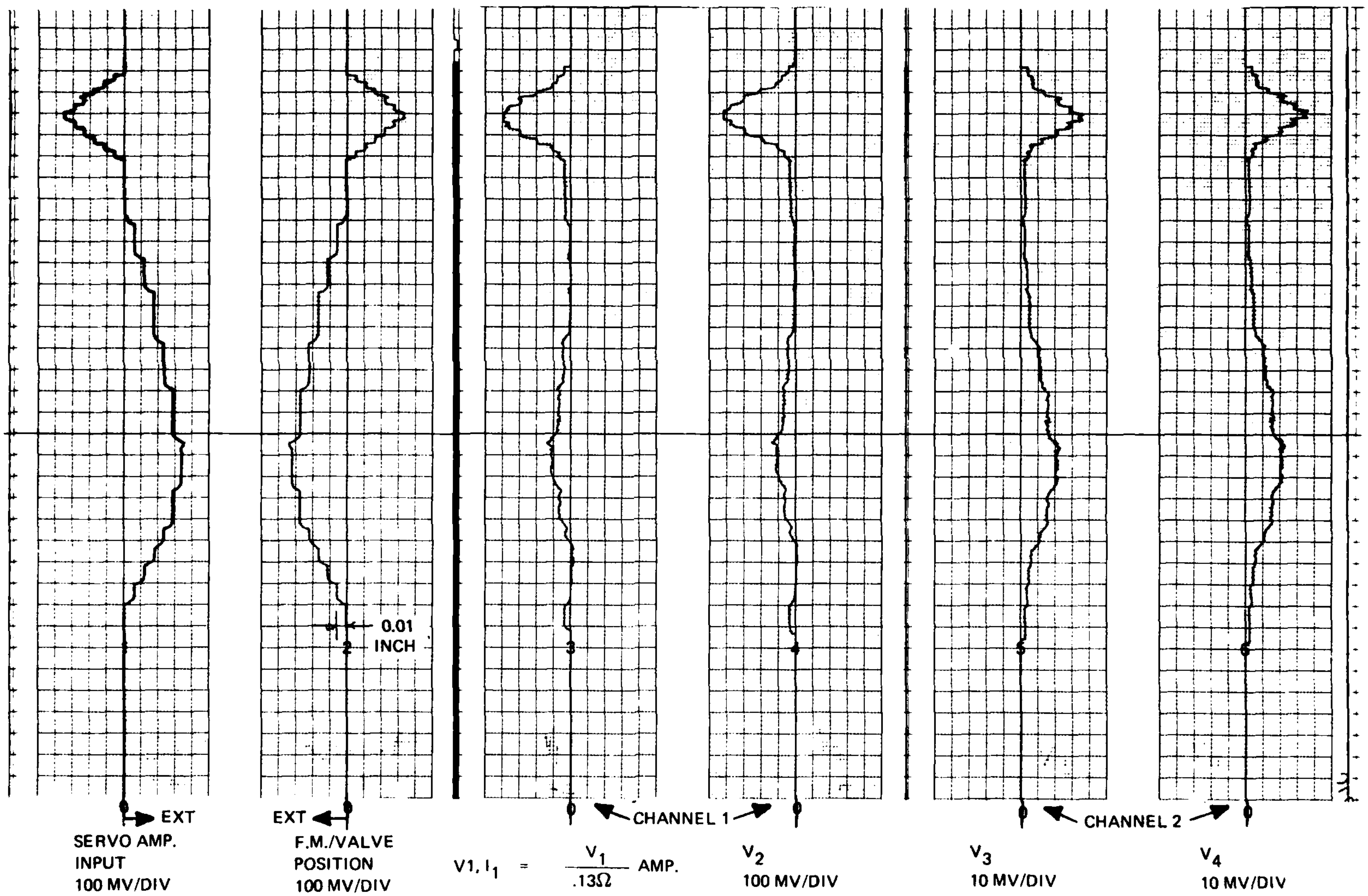


Figure 17. Two Channel, Four Coil Position Gain Recording

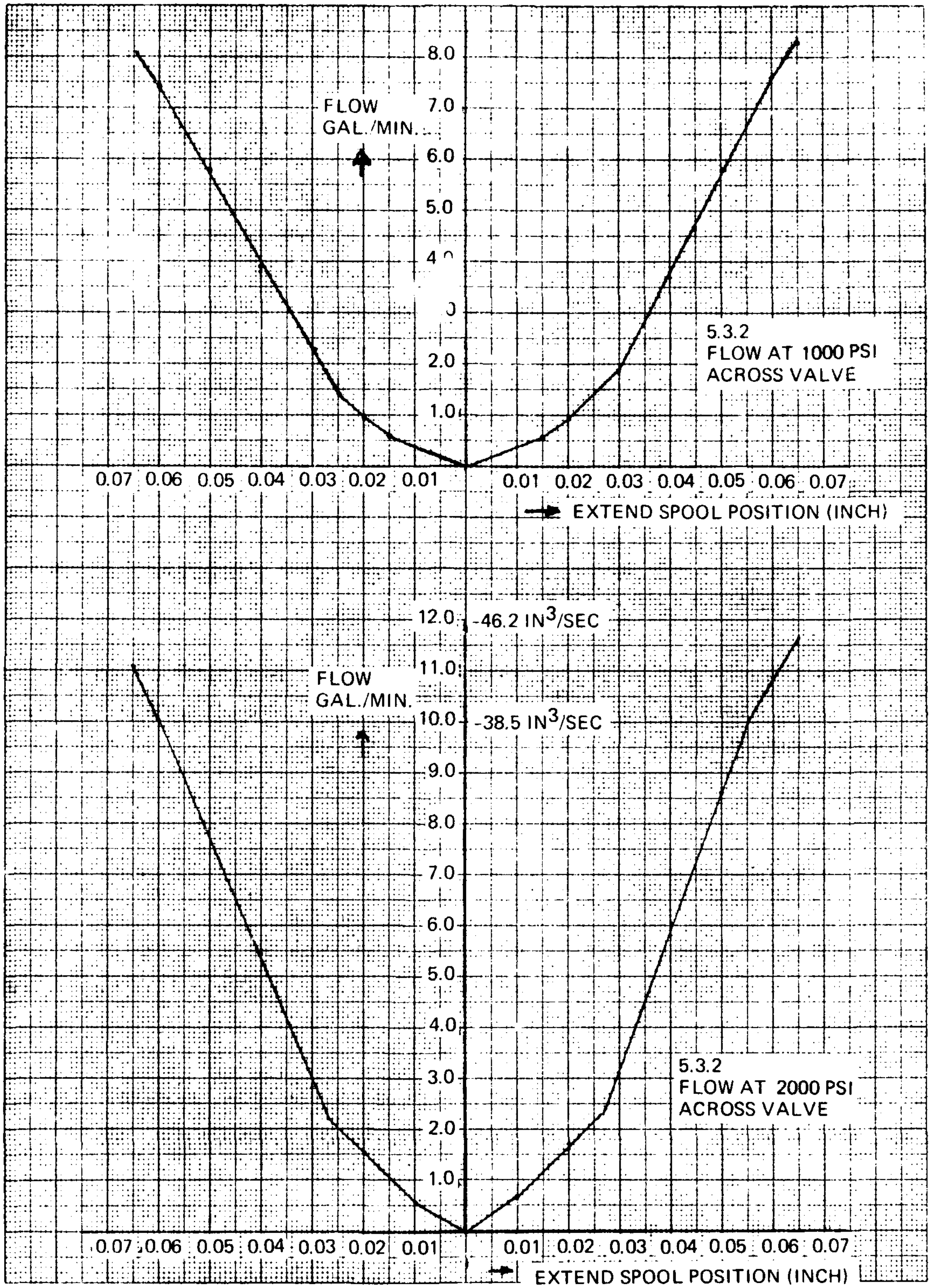


Figure 18. Control Valve Flow vs Force Motor/Spool Position

5.3.3 CLOSED LOOP FORCE MOTOR/CONTROL VALVE FREQUENCY RESPONSE AND THRESHOLD TEST, NO FLOW

The closed loop frequency response test with no flow were conducted according to the test procedure except that the amplitudes were changed from 10% and 50% to 0.010, 0.020, 0.030 inch which corresponds to approximately 15%, 30% and 45% of the ±0.066 inch valve travel. It was decided that these three amplitudes would better define the typical force motor/valve response which varies as a function of amplitude for the selected servoloop gains and frequency response shaping networks. Comparison of Figures 19 and 20 show that the response with one channel (two coils connected) is slightly better due to the higher dc gain of the servoloop. With two channels operating, the servoloop gain that can be used is limited by the mistrack between the force motor/control valve position feedback transducers and servoloop stability considerations. Figures 19 and 20 both show that best response occurs at the lowest amplitude and decreases with increasing amplitude.

5.3.4 CLOSED LOOP FORCE MOTOR CONTROL VALVE FREQUENCY RESPONSE AT 1000 AND 2000 PSI ACROSS VALVE

The frequency response at 1000 psi across the valve is shown in Figures 21 and 22 and in Figures 23 and 24 with 2000 psi across the valve. Two and four coil cases are shown for each valve pressure drop.

Threshold Test

The threshold response of the force motor/control valve is shown in Figures 25 and 26 for two channel and single channel operation at no flow and with flow at 1000 and 2000 psi across the control valve.

From the chart recordings for all conditions it can be seen that the threshold of the force motor is 1 millivolt or less. From the position gain data, the gain from input to output

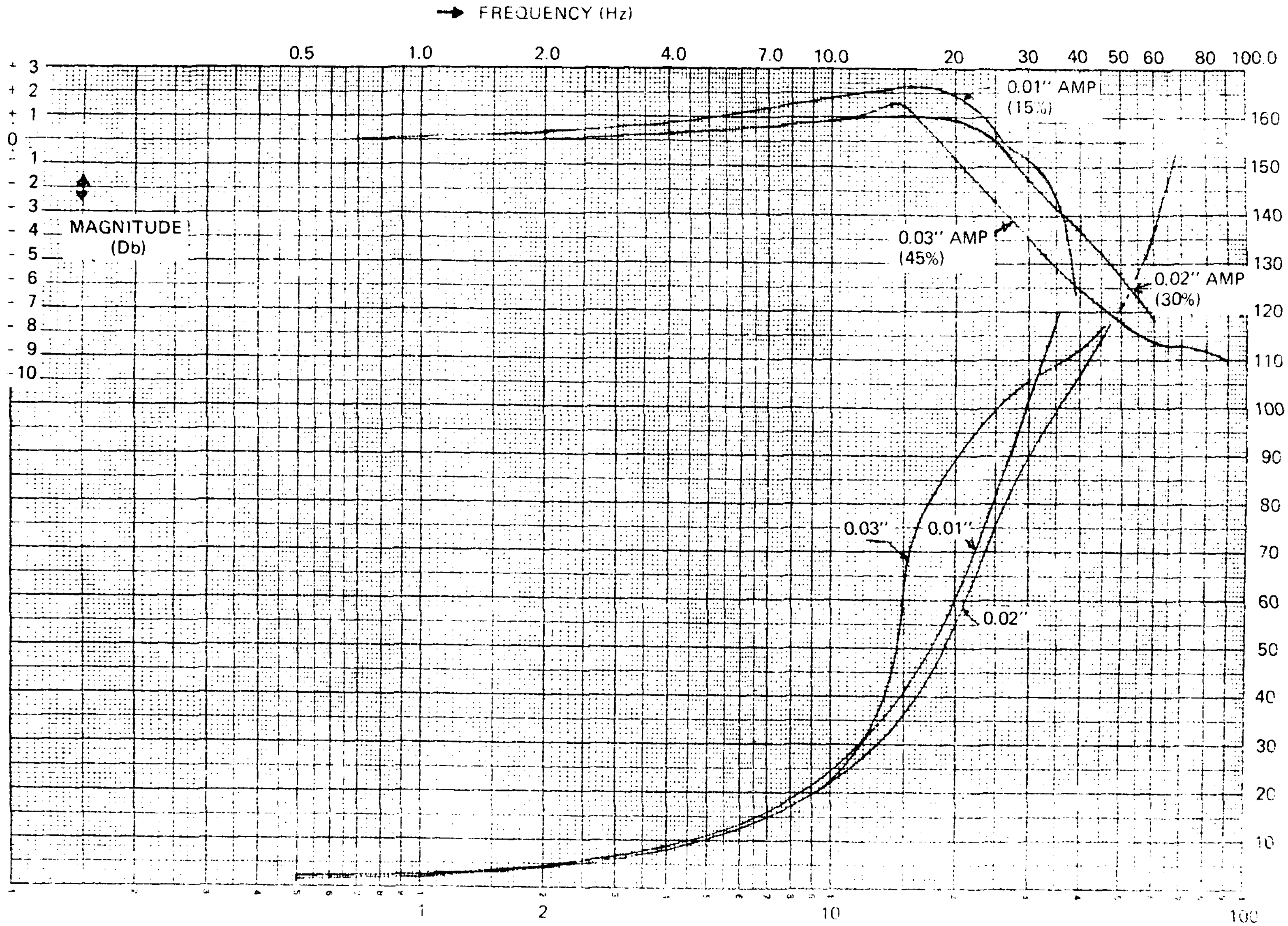


Figure 19. Two Coil, No Flow, Frequency Response of Force Motor Control Valve

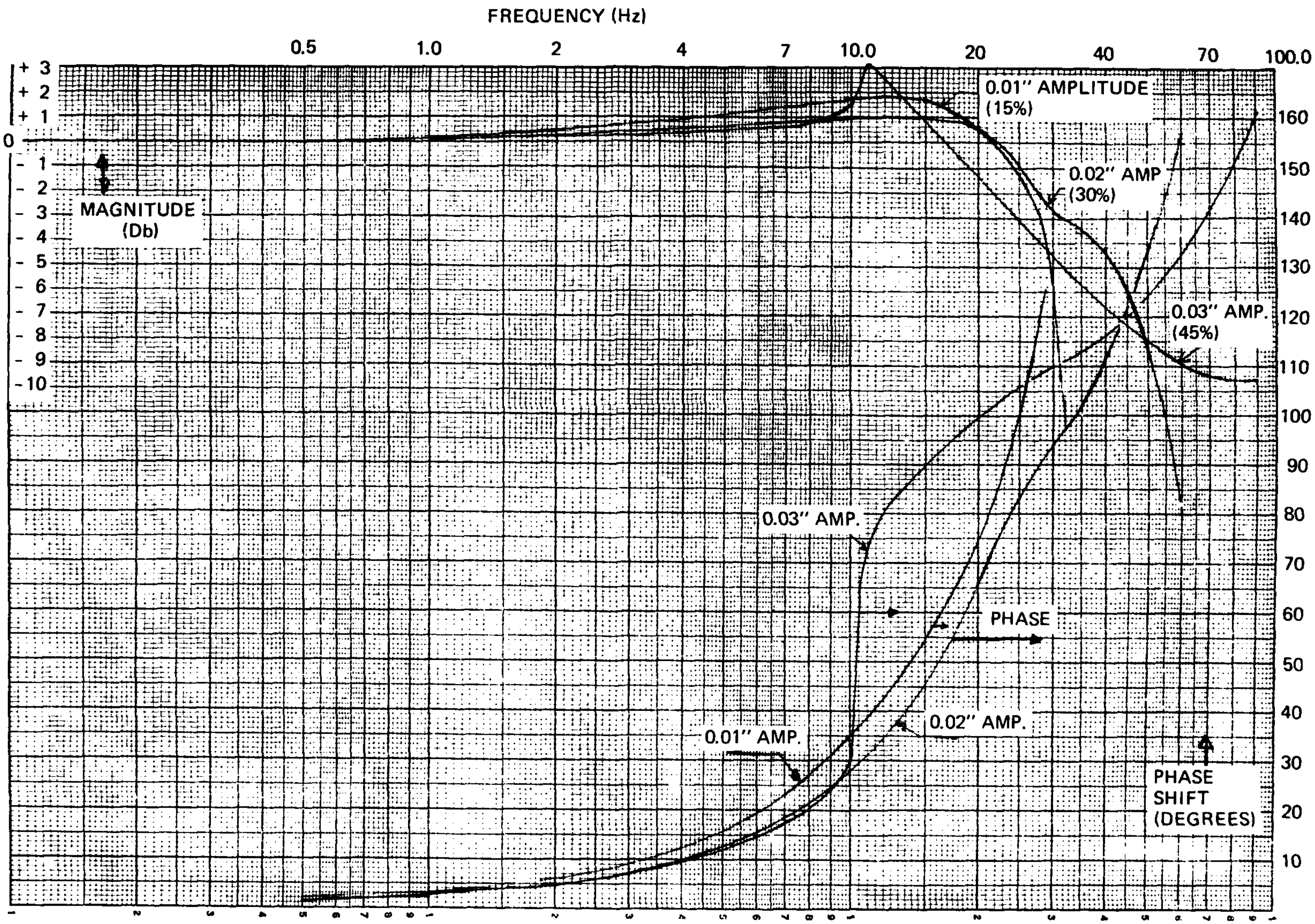


Figure 20. Four Coil, No Flow, Frequency Response of Force Motor/Control Valve

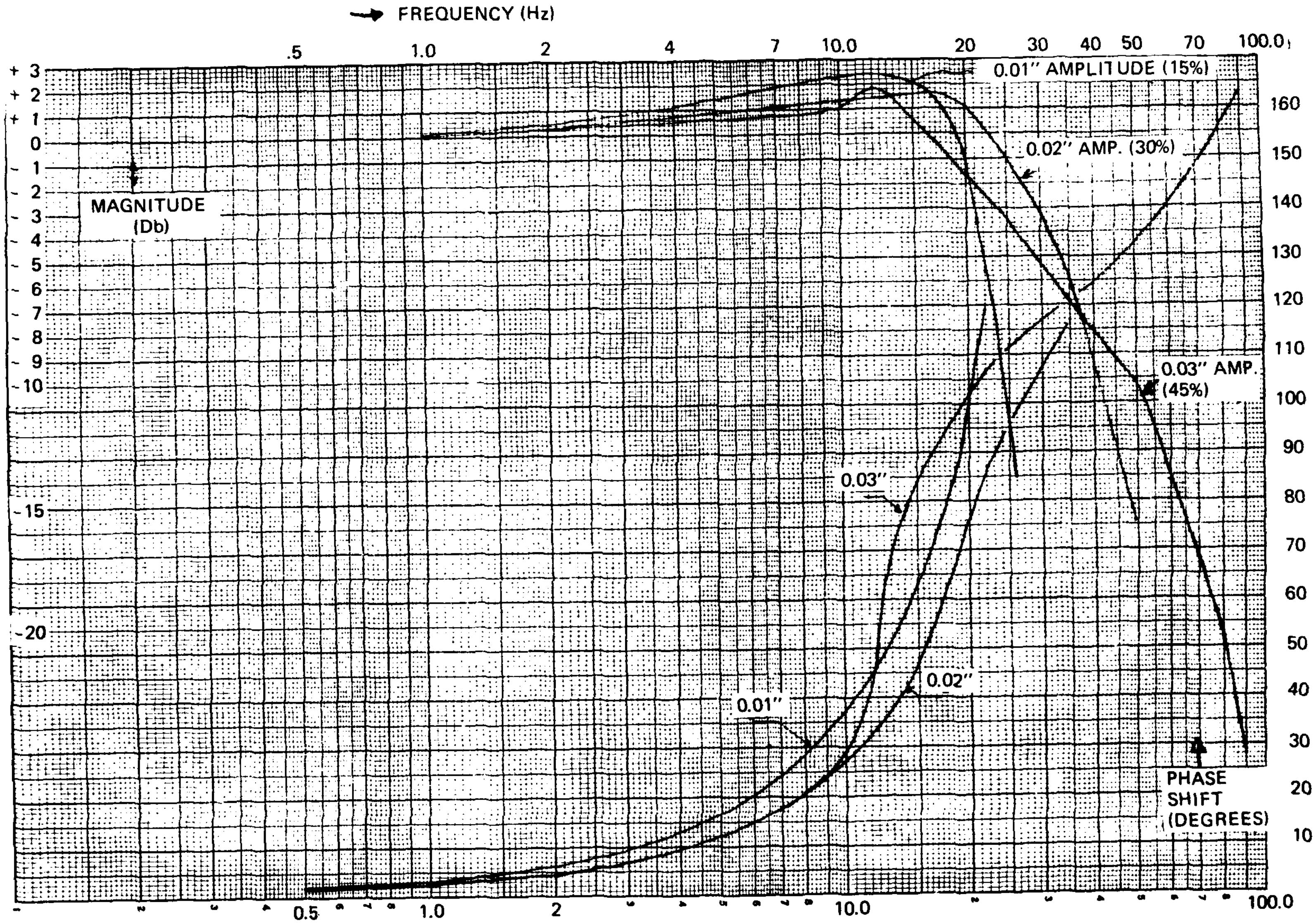


Figure 21. Two Coil, Force Motor/Control Valve Frequency Response, With Flow at 1000 psi Across Valve

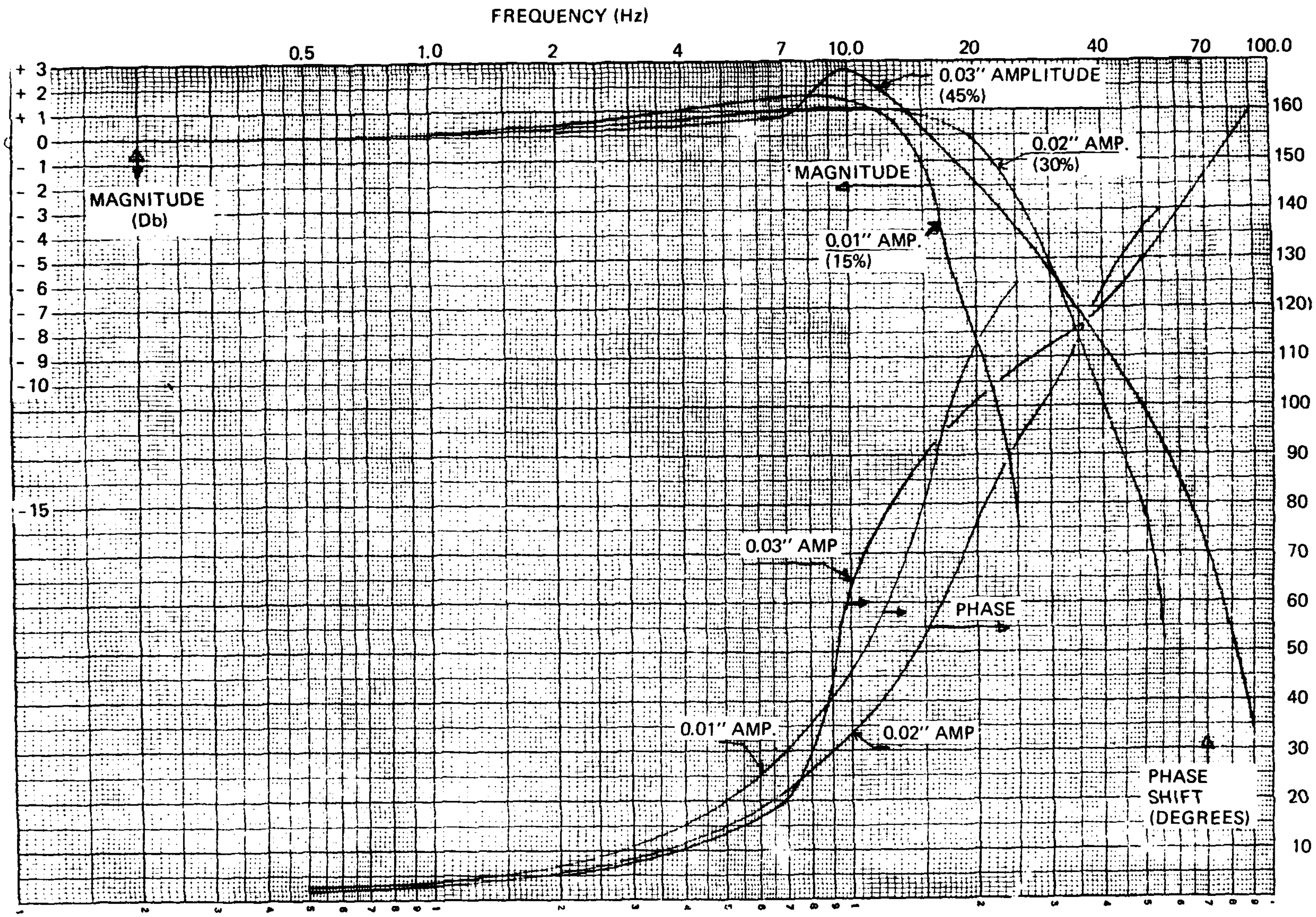


Figure 22. Four Coil, Frequency Response of F.M./Control Valve, With Flow at 1000 psi Across Valve

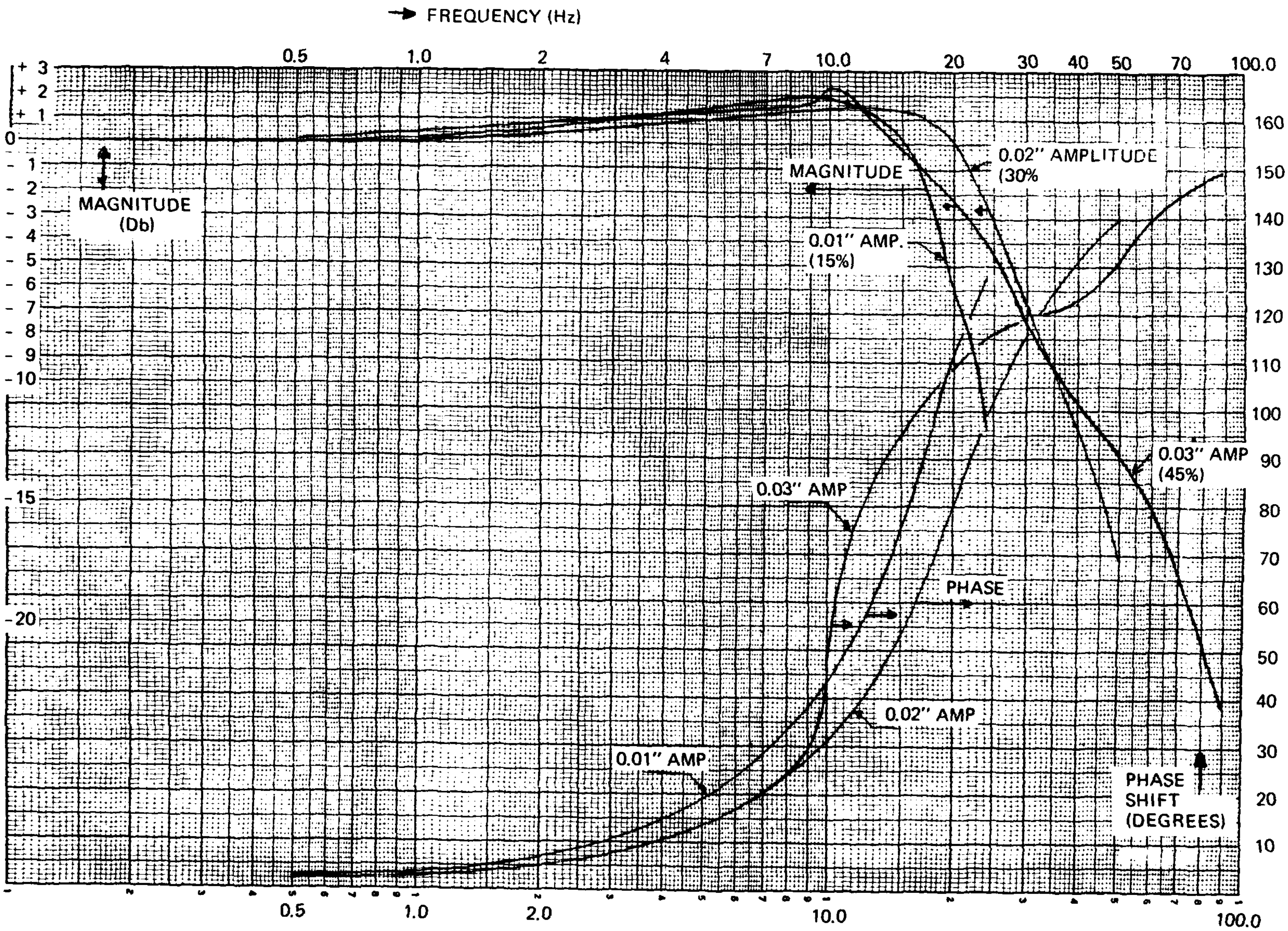


Figure 23. Two Coil Force Motor/Control Valve Frequency Response, With Flow at 2000 PSI

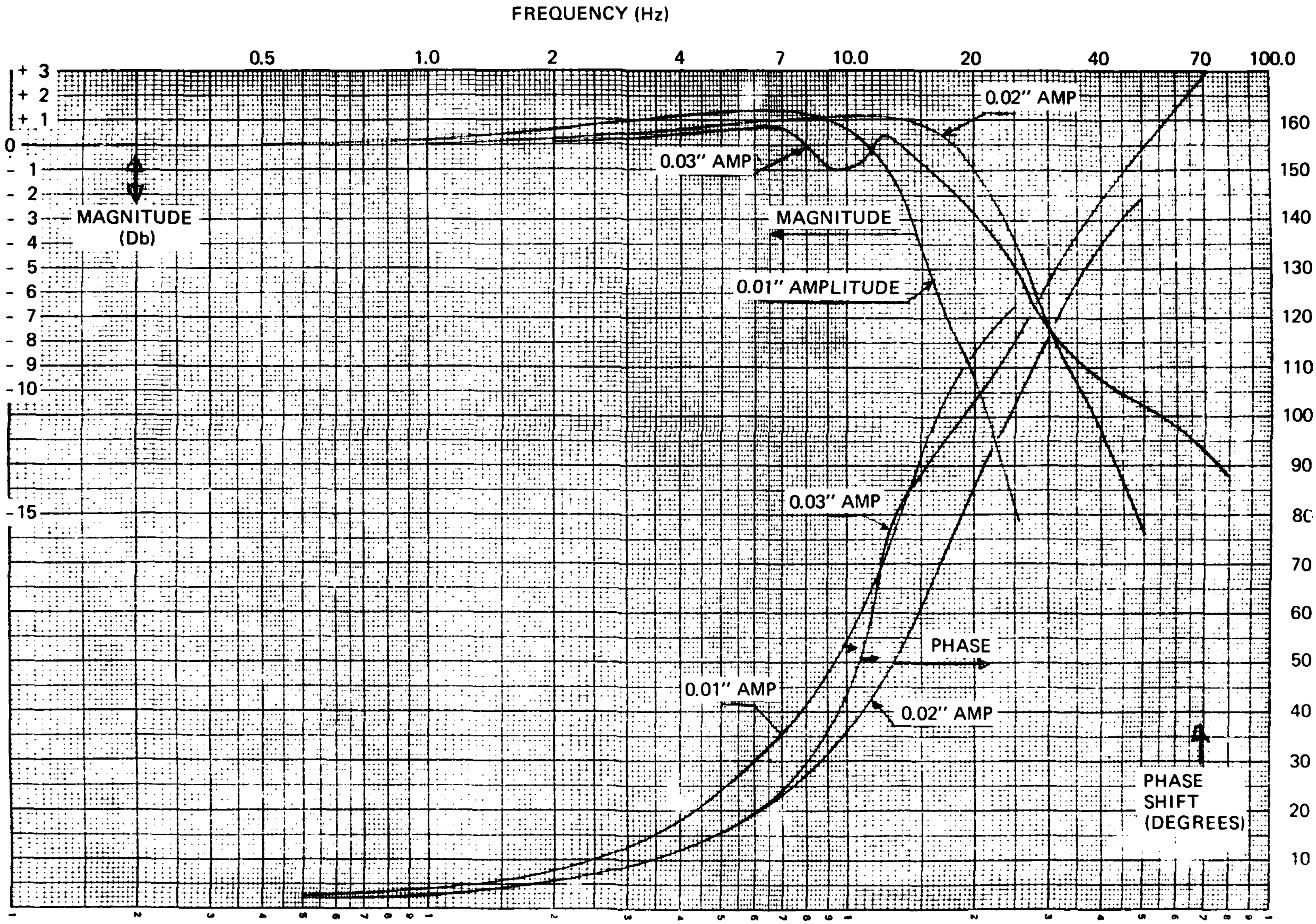


Figure 24. Four Coil at 2000 PSI Across Valve, Frequency Response of F. M./Control Valve

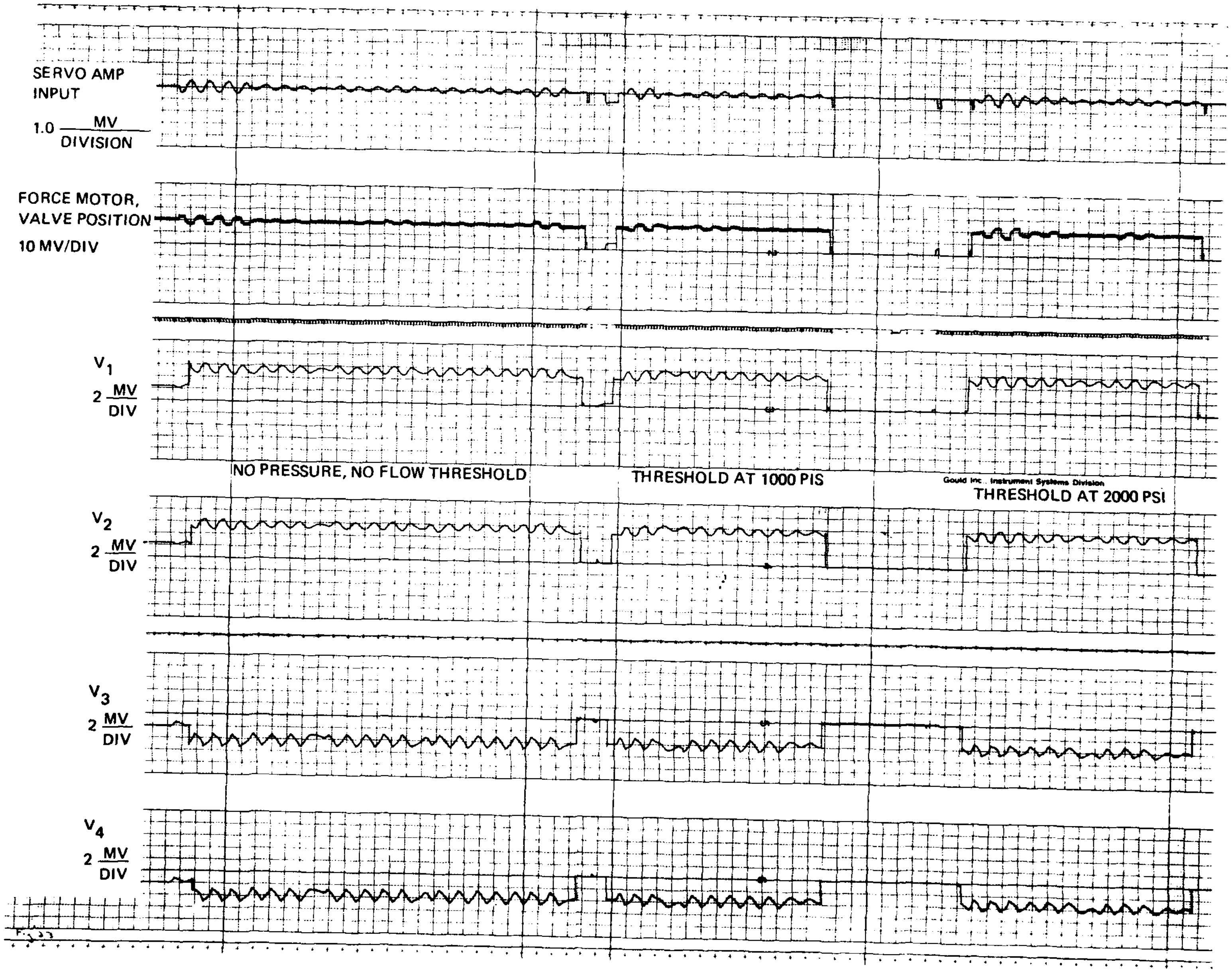


Figure 25. Two Channel, Four Coil Threshold at No Pressure and at 1000 and 2000 psi

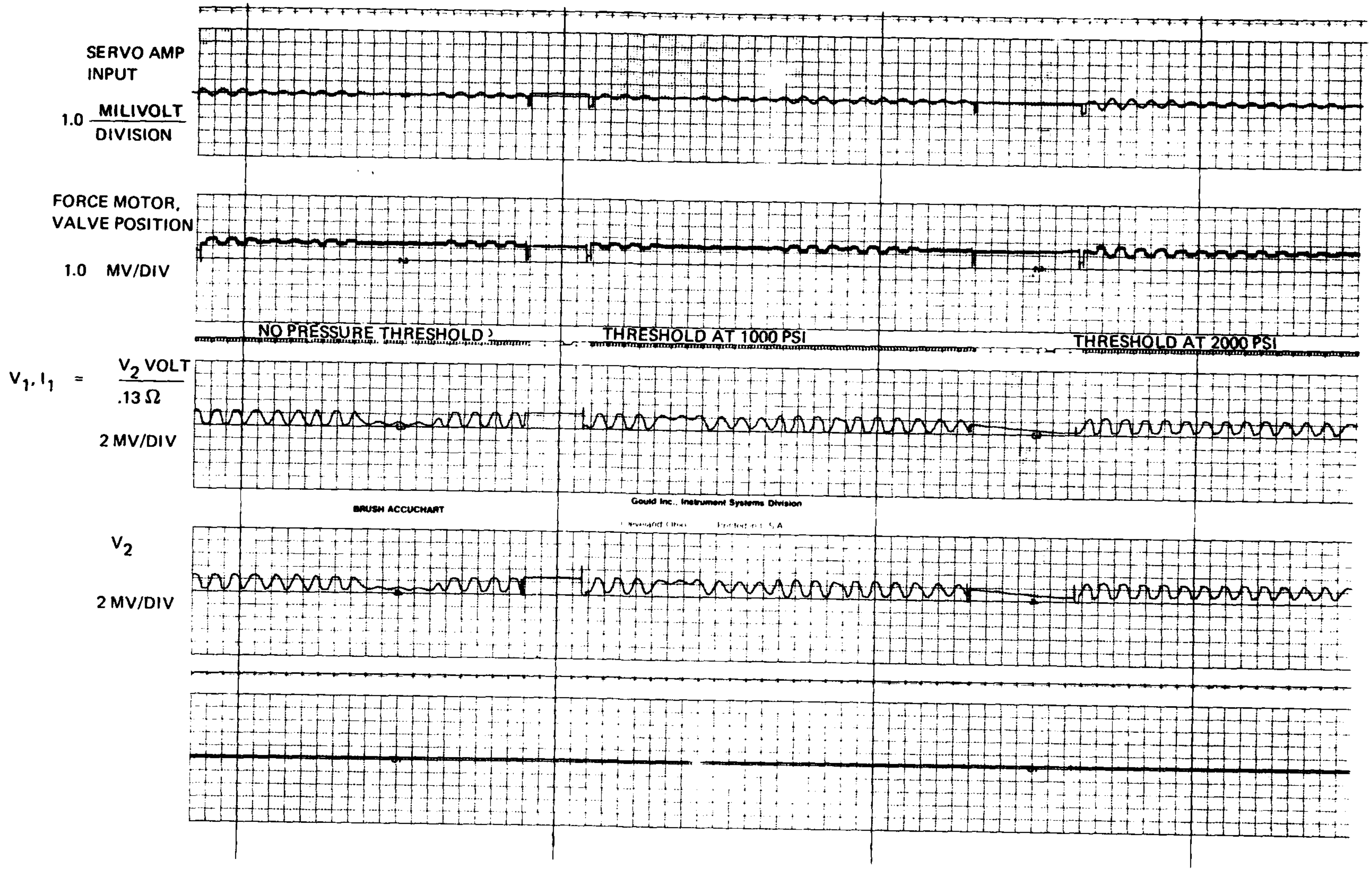


Figure 26. Single Channel Threshold at No Pressure and at 1000 and 2000 psi

position is 29.0 volts/inch. Thus, the threshold as a percent of a ±0.066 inch force motor stroke is given by

$$\text{Threshold} = \frac{0.001 \text{ volt}}{29 \text{ volt/inch}} (0.066 \text{ inch}) \times 100 = 0.0522\%$$

5.3.5 AILERON ACTUATOR OUTPUT VELOCITY, OPEN LOOP VS F.M./CONTROL VALVE POSITION AT 1000, 2000 AND 3000 PSI ACROSS ACTUATOR AND CONTROL VALVE

Before closing the power actuator servoloop the output velocity of the F-4 aileron actuator as a function of force motor/control valve position was measured per Section 5.3.5 of the test plan. The results of this test are presented in the plots shown in Figure 27. The highest no load velocities occur at 3000 psi across the valve as is shown in the curves. The curves show the non-linear velocity gain of the aileron actuator which has an effect on the frequency response of the actuator. In the region of ±0.022 inch of valve stroke there is a difference in extend and retract velocity gain due to the large difference between extend retract piston area. For determining the actuator outer servoloop gain required to obtain a no load 5 Hz bandwidth, the low retract velocity gain at 3000 psi of 76.67 (in/sec)/inch was used in loop gain calculations.

TEST CONCLUSIONS

The laboratory tests performed on the breadboard force motor and an F-4 aileron control valve indicate satisfactory operation in terms of force, linearity, frequency response and threshold for use as an aircraft control driver actuator. The evaluation included both two channel and one channel operation.

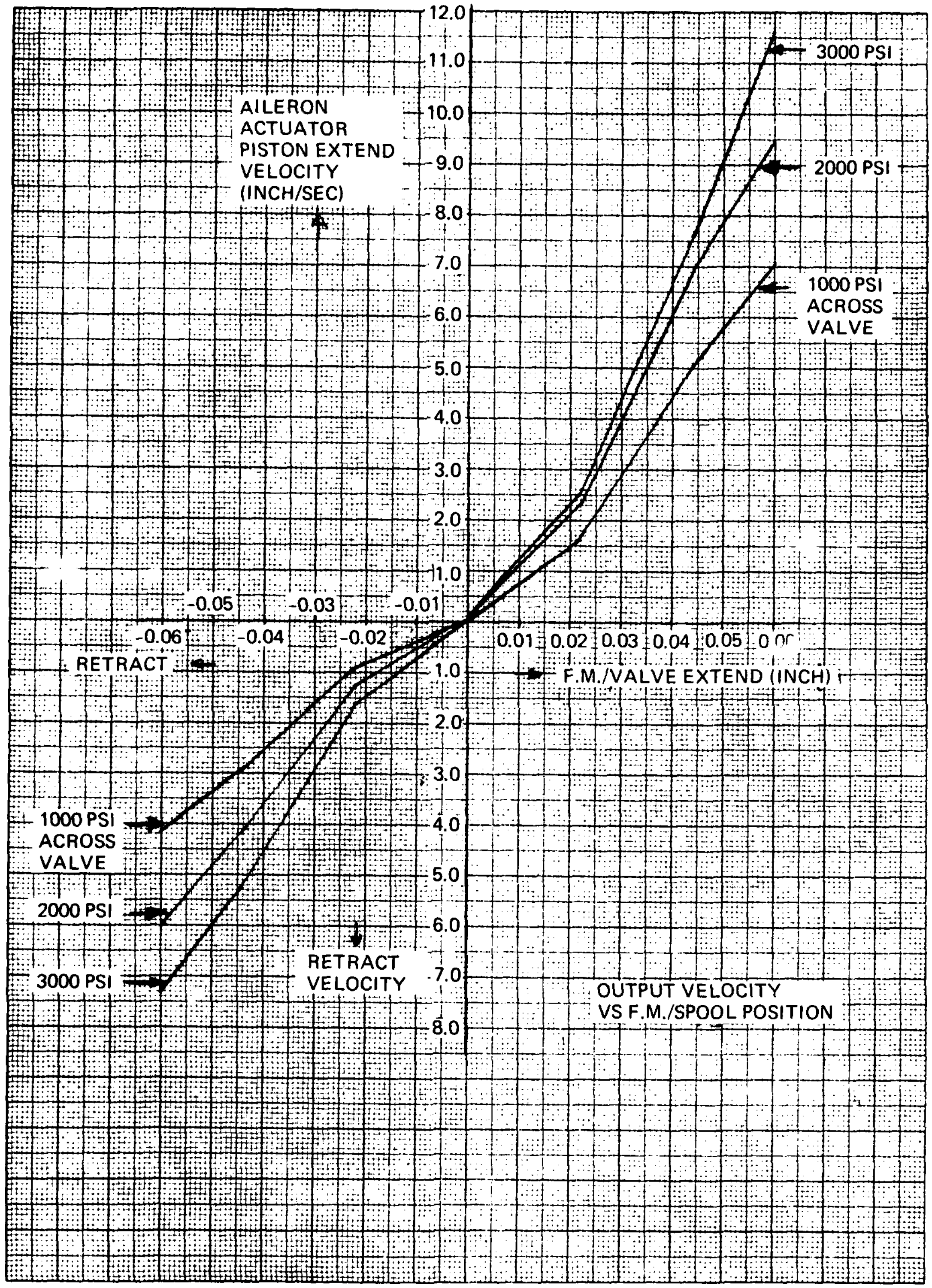


Figure 27. Aileron Actuator Output Velocity at 1000, 2000 and 3000 Pound/in^2 Across Control Valve

ELECTRONICS

REQUIREMENT

The electronics for the direct drive actuator are required to perform the functions listed:

1) Provide current driver for force motor coils.
2) Close the force motor position loop.
3) Close the main ram position loop.
4) Be capable of operation after a single failure.
5) Provide power for internal circuits and excitation for the position transducers on the actuator and on the cockpit lateral stick.

REDUNDANCY MANAGEMENT

The three direct electrical linkage actuation system configurations considered are presented in Figure 28. All of the schemes are designed for fail operational performance by detecting differences in current to the coils of the valve driver motor and isolating the failure by disconnecting the coil or coils in the failed channel. Any single failure in a command input, feedback input or signal path that results in one coil current differing from the other or others above a given level will be detected.

Table 1 presents a listing of comparison parameters and the results of evaluating the parameter for each of the three configurations. From Table 2 it can be seen that system C requires the lowest number of aircraft wires while both B and C require only two aircraft electrical power supplies. If an aircraft has only two independent sources of electrical power available, a significant cost could be incurred to provide another supply to operate the third channel of system A.

System C has the smallest number of stick position and actuator feedback LVDT's. System A has the least number of signal path circuits but the most fail detect circuits and also requires cross channel buffering of the signals used for failure detection.

The reliability of the three system configurations is shown in Table 1, and it can be seen that the dual duplex (configuration B) has a slightly better reliability. The reliability computations were based on the failure rates of the functions in the system as presented in Table 2. For comparison purposes, the power actuator was assigned a zero failure rate since it is common

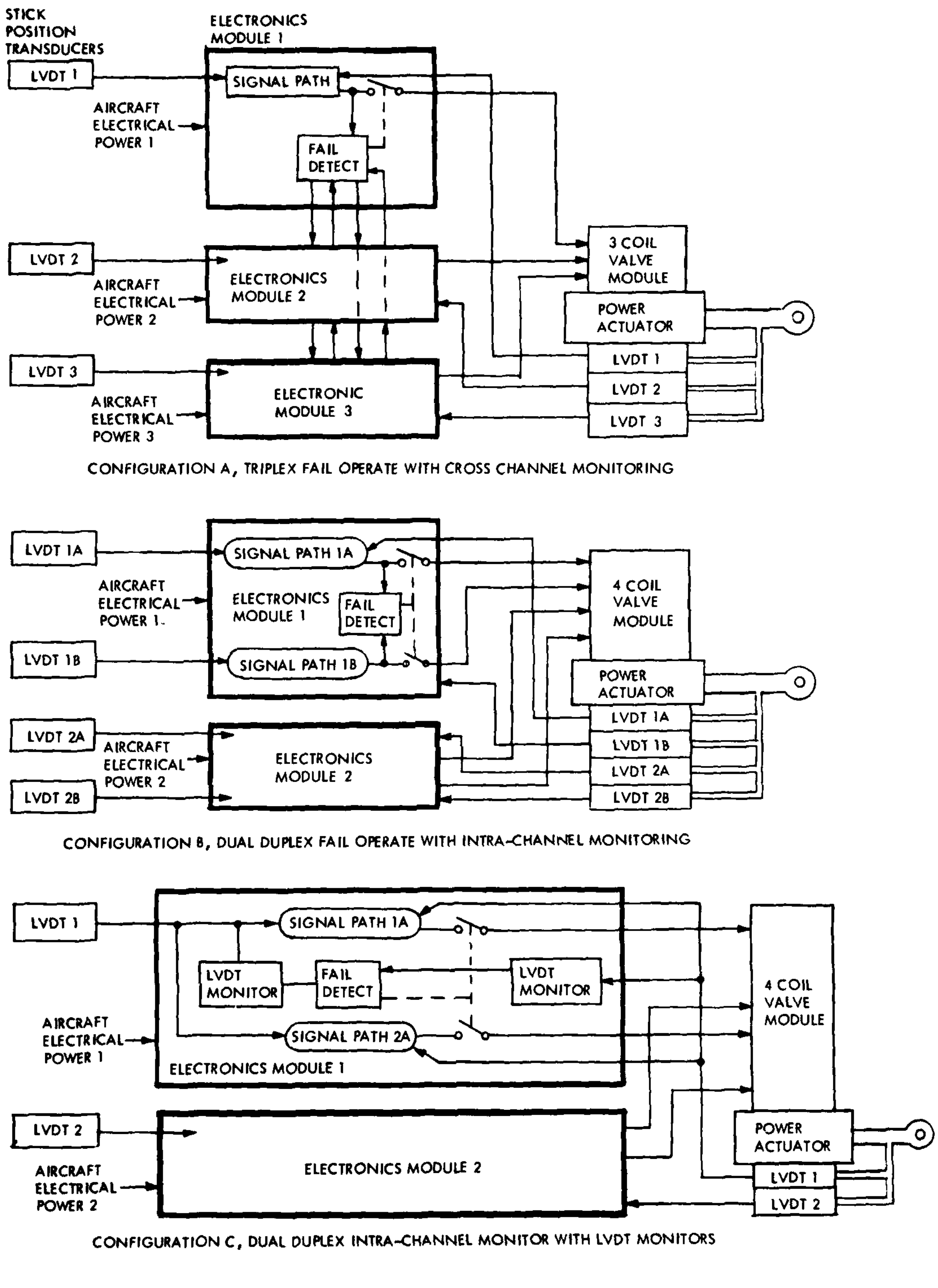


Figure 28. Fail Operate Actuation System Configurations

TABLE 1

COMPARISON OF FAIL OPERATE ACTUATION SYSTEM CONFIGURATIONS

	Comparison Parameter	Configuration A Triplex	Configuration B Dual Duplex	Configuration C Dual Duplex with LVDT Monitors
1.	Number of Aircraft Wires	52	40	32
2.	Number of Required Aircraft Electrical Power Supplies	3	2	2
3.	Number of Electronic Modules and Internal Power Supplies	3	2	2
4.	Number of Stick Position LVDT's	3	4	2
5.	Number of Actuator Feedback LVDT's	3	4	2
6.	Number of Signal Path Circuits.	3	4	4
7.	Number of Fail Detect Circuits	3(more complex than dual)	2	2+2 LVDT monitors
8.	Cross Channel Buffering	Necessary	None	None
9.	Reliability for a Two Hour Mission Excluding Power Actuator			
	Mission (1 Failure)	$1-3.48 \times 10^{-4}$	$1-3.28 \times 10^{-4}$	$1-3.72 \times 10^{-4}$
	Flight Safety (2 Failures)	$1-4.04 \times 10^{-8}$	$1-2.69 \times 10^{-8}$	$1-3.48 \times 10^{-8}$
10.	System MTBF (Hours) Excluding Actuator	5, 742	6, 086	5, 361
11.	Built In Test Function	Separate BIT Computer	Tests can be conducted in each module controlled by a BITE Panel	
12.	Maintenance	LRU Isolation more ambiguous due to cross channel monitoring	Simple LRU Isolation	LRU Isolation better due to LVDT Monitors
13.	Vulnerability to Broken LVDT Probe and Partial LVDT Winding Shorts	Fail Operate	Fail Operate	Not Fail Operate Dual Load Path LVDT probes and mechanical connections can make failure mode extremely remote. Partial LVDT winding shorts in low voltage LVDT's is extremely remote.

to all three systems. The reliability was computed using the following formulas for triplex and dual systems:

Triplex

Mission Rel. $= R_M = (1\text{-}Q) = 1\text{-}3Q_C = 1\text{-}3(1\text{-}e^{-\lambda_C T})$

Flight Safety Rel. $= R_{FS} = 1\text{-}Q = 1\text{-}(3Q_C^{\;2} - 2Q^3)$

Dual

$R_M = 1\text{-}Q = 1\text{-}2Q_C = 1\text{-}2(1\text{-}e^{-\lambda_C T})$

$R_{FS} = 1\text{-}Q = 1\text{-}Q_C^{\;2} = 1\text{-}(1\text{-}e^{-\lambda_C T})^2$

where λ_C = Channel Rate Per Hour
T = Mission Time in Hours
Q_C = Probability of Channel Failure

TABLE 2

FAILURE RATE COMPARISON

Function/Channel/System	Function/Channel/System Failure Rates Per Million Hours — Configuration: A(Triplex)	B(Dual)	C(Dual)
Stick LVDT	1.00	2.00	1.00
Electronics			
Power Supply	7.62	7.62	7.62
Signal Path	23.59	47.18	47.18
Failure Detect	23.84	21.35	34.47
Electronics Subtotal	55.05	76.15	89.27
Coil of Direct Driver	1.00	2.00	2.00
Feedback LVDT	1.00	2.00	1.00
Power Actuator	0.00	0.00	0.00
TOTAL Channel = λ_C	58.05 x3	82.15 x2	93.27 x2
TOTAL System	174.15	164.30	186.54

The system MTBF was computed and Table 1 shows that the dual duplex (configuration B) has the highest mean time between failure.

Table 1 presents some qualitative assessments of the BITE function and maintainability based on experience with the SFCS program 680J quadruplex, dual fail operate cross monitored system and the HLH prototype, triplex, dual fail operate intra-channel monitored system.

The last item presented in Table 1 points out particular failure modes where the triplex and dual duplex systems are fail operate while the dual system with self-monitored LVDT's is not.

Based on such items as the required number of aircraft power supplies, system reliability, MTBF, BITE function and maintainability assessment, invulnerability to physical damage to a single LVDT, the dual duplex (configuration B) system was selected for use in this application.

BREADBOARD ELECTRONIC TESTING

Figure 29 is a block diagram of the dual duplex control system. Starting at the actuator, it can be seen that a four coil direct drive force motor is used to drive the dual tandem control valve of the F-4 aileron surface dual system, parallel four cylinder servoactuator. The force motor/control valve position is sensed by two LVDT's whose outputs are fedback to the servoamplifiers in each channel to form an inner position servoactuator. The two LVDT's are also self monitored to detect loss of power and open or shorted input or output coils in the LVDT. Aileron actuator position is sensed by the four LVDT's and fedback to the servoamplifiers in the dual channel electronic control module. The control electronics consists of two independent (duplex) channels with two (dual) signal paths per channel. If the difference between the two servoamplifier outputs in each channel exceed a predetermined level, the comparators and bipolar failure detect circuits in the fail detect logic will operate the relay and disconnect the direct drive motor coils from the servoamplifier output. Thus, each of the two duplex channels can detect and isolate any single failure in one of the two signal paths in a channel.

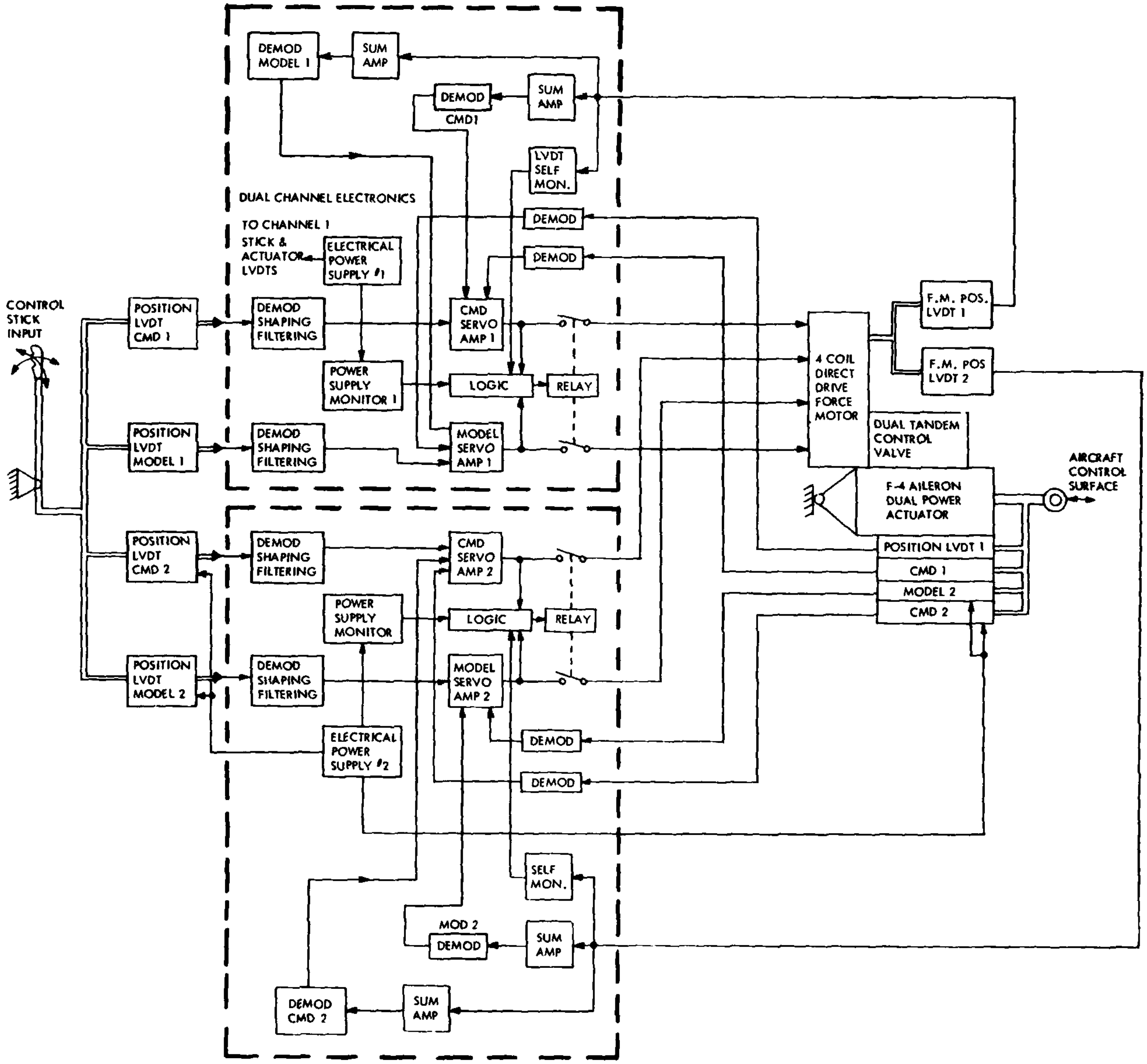


Figure 29. Dual Duplex/Fail Operate Direct Drive Actuation System

The electrical schematic of one of the dual control electronic channels is shown in Figure 30. The schematic shown was fabricated for use in breadboard testing. The manual gain change switch and the averaging resistors which cross tied the error signal in each path of the electronics were added after closing the power actuator servoloop.

When the power actuator servoloop was first closed, it was observed that the actuator had a limit cycle oscillation.

By increasing the inner loop force motor feedback gain, the oscillation was reduced. Thus, the conclusion was that valve spool friction was the probable cause. Since plastic cap strips were added over the O-ring seals in an effort to reduce friction, it was decided that they should be removed to determine if any improvement would result. After the cap strips were removed the magnitude of the oscillation was reduced. The conclusion was that the cap strips over the O-ring had increased the squeeze and resulted in an increase in force on the plastic cap strips. Although, the friction coefficient was probably lower, the total friction force was higher due to the increase in squeeze. To further reduce the oscillation the force motor servoloop gain was increased until the oscillation was reduced to ± 0.0015 inch (0.003 inch peak to peak) as observed on a dial indicator which measured pistion motion with respect to the cylinder. To maintain the residual oscillation at a low level with single channel operation, the inner loop force motor servoloop gain was increased by a factor of three through opening of the manual gain change switch. To reduce the residual oscillation to zero, a sinusoidal input with a frequency of 45 Hz was summed to each servoamplifier to cause a very low amplitude force motor output which effectively removed the friction effects, and was not observable on the power actuator output.

The actual servo loop gains and frequency response shaping transfer functions used in the breadboard test is shown in the System Block Diagram in Figure 31.

From the diagram in Figure 31 it can be seen that the open loop gain (K_I) and transfer function of the force motor servoloop is given by:

$$K_I \text{ (4 coil)} = 4\left[(29 \text{ V/inch})\left(\frac{86.6}{3.16}\;\frac{(S/250+1)}{(S/0.5+1)(S/500+1)}\right)\left(\frac{2.26 \text{ amp/volt}}{S/275+1}\right)\right](0.064)$$

$$K_I \text{ (2 coil)} = 2\left[(29)\left(\frac{86.6}{3.16}\;\frac{(S/250+1)}{(S/0.5+1)\,(S/500+1)}\right)\left(\frac{6.78}{S/275+1}\right)\right](0.064)$$

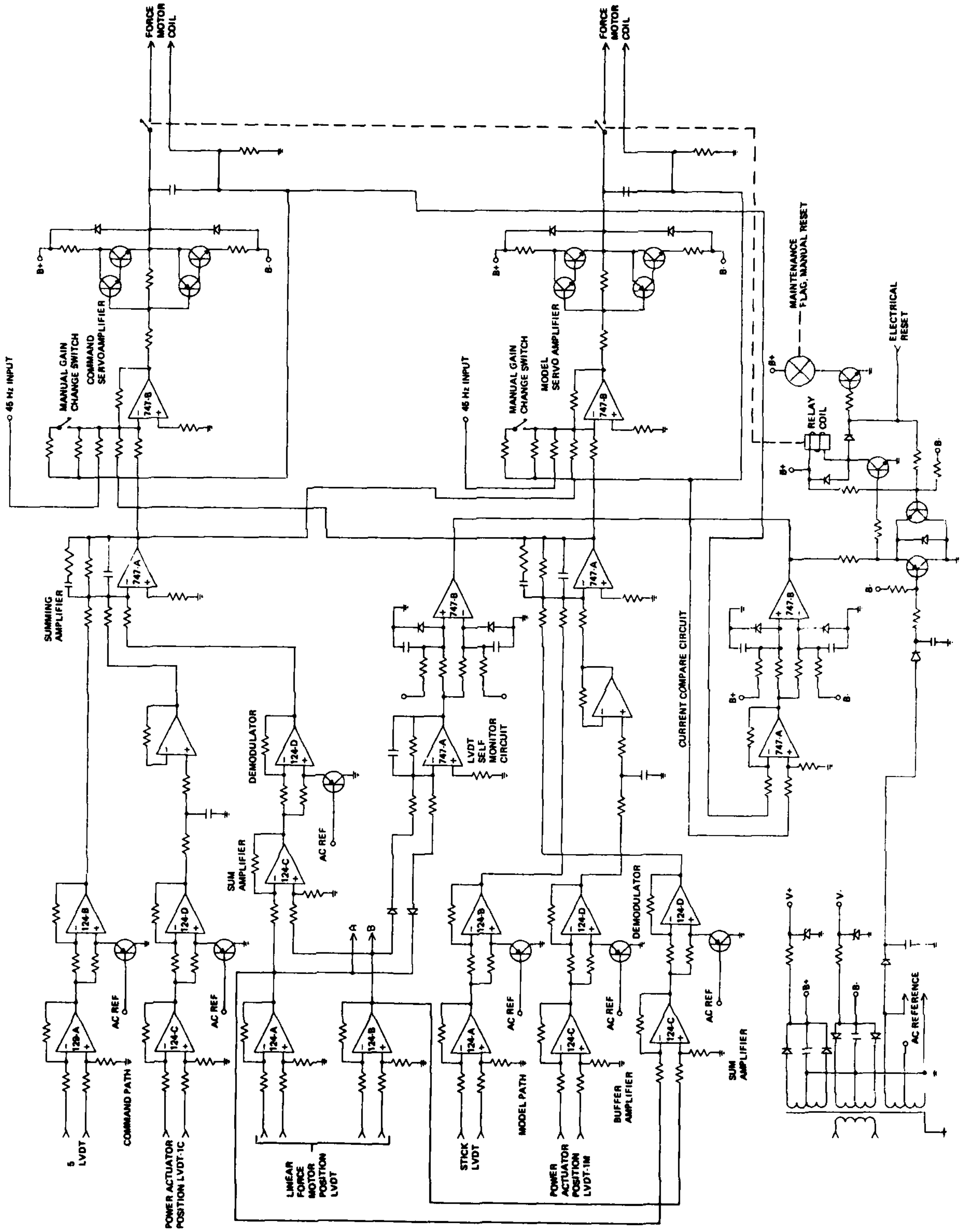


Figure 30. Direct Drive Actuator Control Electronics Schematic, Single Channel

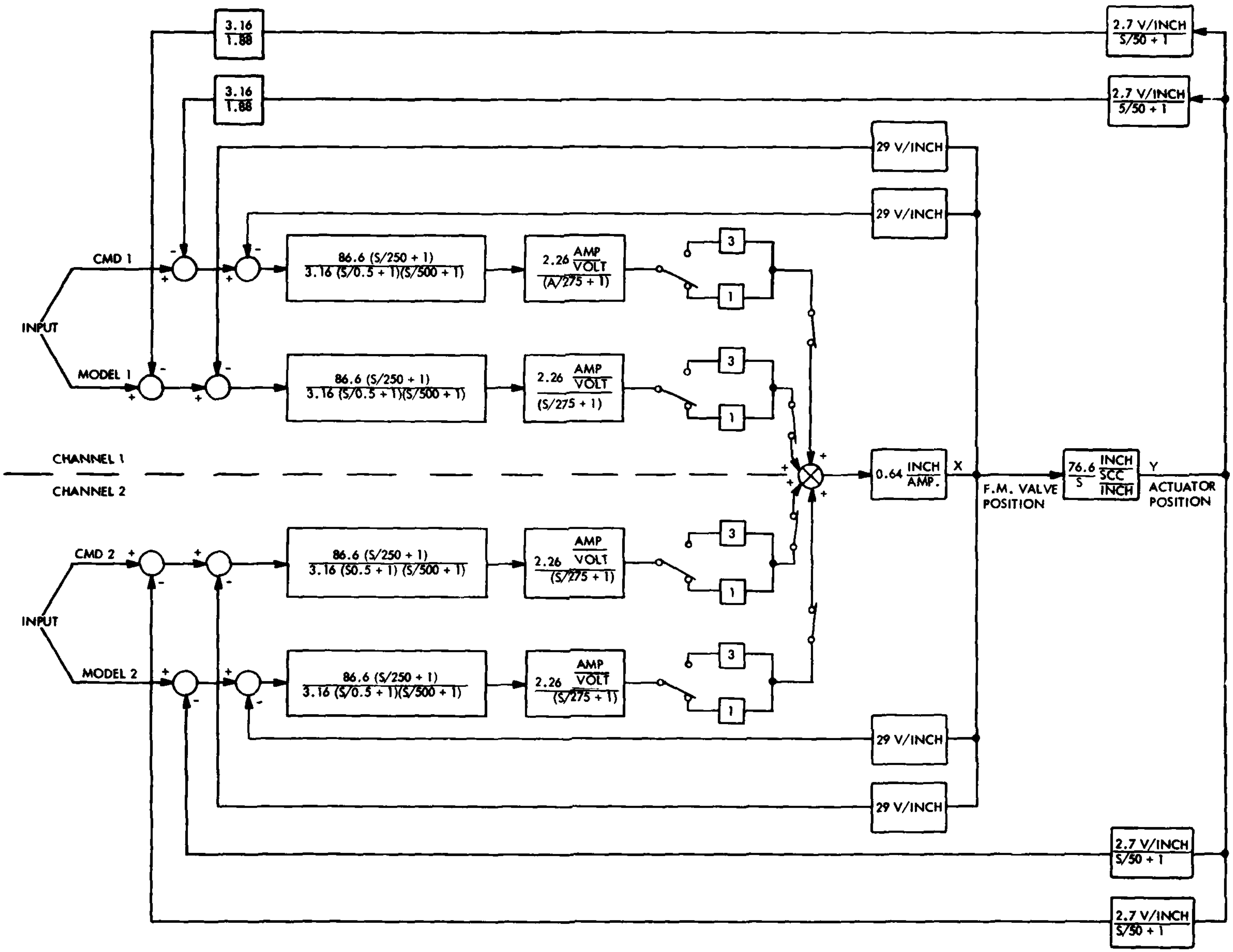


Figure 31. Breadboard Control System Gains and Transfer Function Diagram

The open loop gain (K_O) and transfer function of the outer loop is given approximately by the following expression for either single or two channel operation.

$$K_0 = 2\left(\frac{2.5 \text{ V/inch}}{S/50 + 1}\right)\left(\frac{3.16 \text{ V}}{1.88 \text{ V}}\right)\left(\frac{1 \text{ inch}}{29 \text{ volts}}\right)\left(\frac{76.7 \text{ inch/sec.}}{S \quad \text{inch}}\right) = \frac{24/\text{sec.}}{S(S/50+1)}$$

The above expression, which deletes the closed loop transfer function of the force motor, indicates that the closed loop power actuator frequency response will be dominated by a pair of complex closed loop roots at about 30 rad/sec. (approx. $5H_z$) and a lead at 50 rad/sec. The breadboard power actuator frequency response data given in Figures 37 and 38 of this report confirm this statement.

The high gain of the inner force motor servoloop, below 0.5 rad/sec., required to minimize the limit cycle oscillation of the closed loop power actuator, tends to reduce the force motor stiffness with both channels operating.

This reduced stiffness results from the difference in null and tracking of two force position transducers. When operating on a single channel with only one position transducer and increased servoloop gain the force motor stiffness is higher since no current (equivalent force) fight can occur.

The breadboard test results have confirmed that the present force motor stiffness with both channels operating is satisfactory.

To increase force motor stiffness with both channels operating and allow for mistrack in the inner and outer loop feedback a change to the active/on-line concept was made. This concept used in the control system for another triplex/dual fail operate actuator development program uses a different approach to the gain switching after failure than has been implemented in the present breadboard system. A block diagram of the change in the system is shown in Figure 32.

This diagram shows the limited and filtered feedback path around the servoamplifiers in channel 2. Thus channel 2 is the on-line channel while channel 1 with no feedback is the active channel in command of the output.

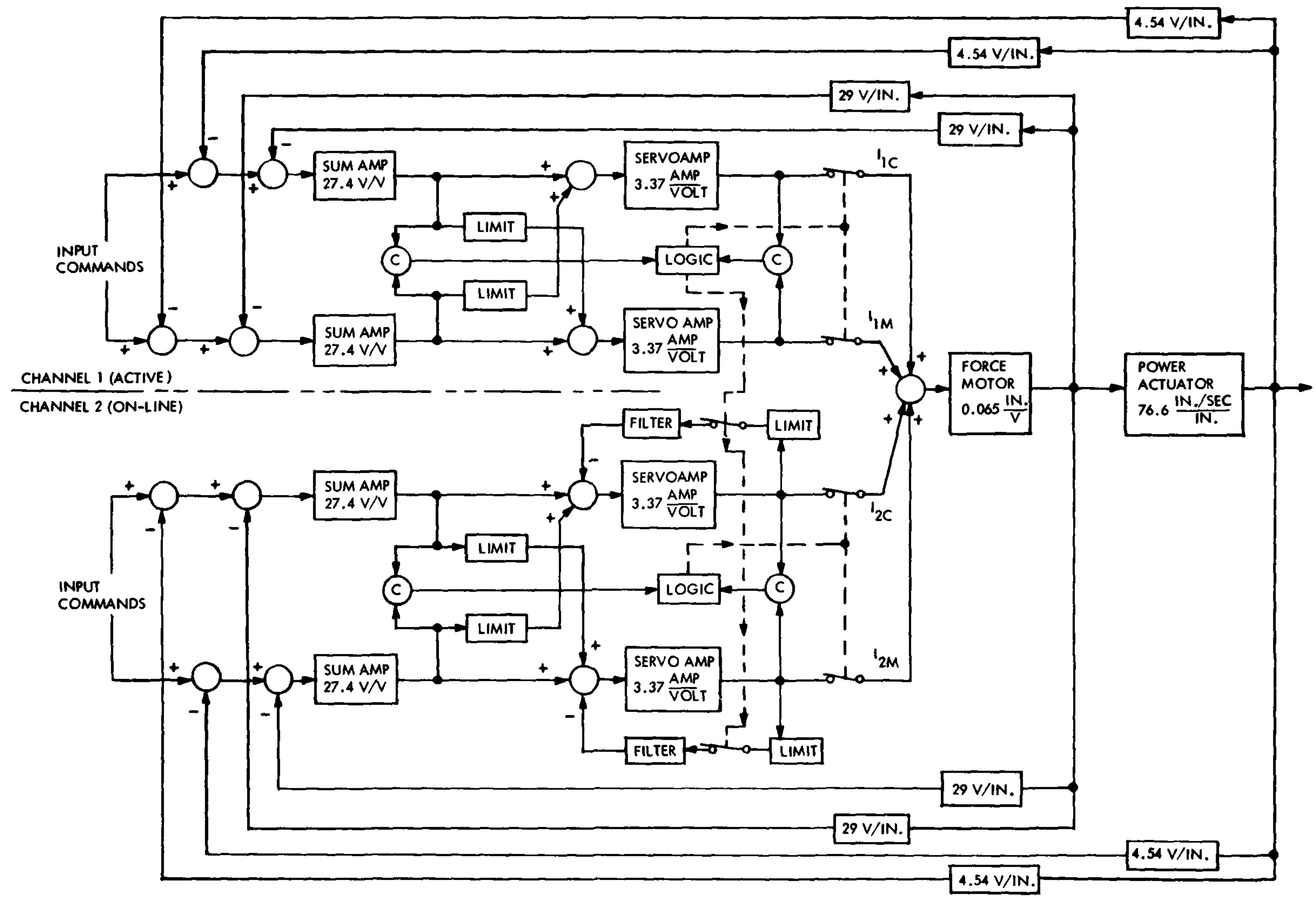


Figure 32. Modified Breadboard Control System Block Diagram

The diagram also shows the added limiters and the additional comparator that must be added due to the averaging of the error outputs of the summing amplifiers into each signal path servoamplifier within a channel.

In the active/on-line concept both channels have the gain required to meet the closed loop response with a single channel operating. However, this can produce a large current or force fight, so one of the channels is made on-line by connecting another feedback around the inner loop which is limited and low pass filtered to effectively reduce the current or force gain of the on-line channel at low frequency. Thus, the active channel essentially controls the inner loop output while the on-line channel is reduced in its effectiveness in providing force output until the limit is reached. If a failure occurs in a servoamplifier or some feedback, the limit in the on-line feedback path is achieved and the other three signal paths, one in the on-line and two in the active channel, current sum to oppose the failure until the failed channel is disconnected.

ACTUATOR MODIFICATION

REQUIREMENTS

The F-4 aileron actuators required two modifications.The first to provide a mounting point for the force motor by machining away the input linkage attaching points. The second involves the addition of position transducers on the main ram for position feedback to replace the mechanical input linkage in the original "traveling body" arrangement.

BREADBOARD VS FLYABLE

The breadboard actuator was modified in the same manner planned for the flyable units. Breadboard testing was accomplished, therefore, with an actuator and force motor in the final mechanical and electrical configuration.

TEST RESULTS

TEST RESULTS FOLLOW WHERE PARAGRAPH NUMBERS CORRESPOND TO TEST PROCEDURE PARAGRAPHS OF TEST PLAN INCLUDED AS APPENDIX.

5.4 DIRECT DRIVE ACTUATOR SYSTEM TESTS

The direct drive actuation system tests that have been conducted include position gain, simulated failure, frequency response and threshold using an available dc to dc LVDT for actuator feedback. The actual LVDT's arrived later than expected and could not be installed in time to conduct the system tracking tests called for in the breadboard test plan.

5.4.1 CLOSED LOOP POSITION GAIN TRACKING AND SERVO ELECTRONICS GAIN MEASUREMENTS

For the position gain tests the single actuator position transducer was nulled at approximate mid-stroke of the power actuator which is about ±1.1 inch. The actual full travel of the breadboard aileron actuator is 2.187 inch. The force motor/control valve was not precisely nulled at the exact actuator velocity null so that Figures 33 and 34 show some feedback null voltage for zero input voltage. Figure 30 presents the actuator position gain of output inch and output position feedback volts to the input position command. Figure 34 shows the relationship of output feedback volts to actuator position. Figure 35 presents a chart recording of the input command, output position, force motor position and three of the four force motor currents. Comparison of V1 and V3 associated with channel 2 shows that some current fight occurs due to differences in the electronic gains between the two channels even when a single position transducer is used.

5.4.2 FAULT DETECT LEVEL AND FAILURE TRANSIENT TESTS

Figure 36 presents a simulated failure in one servoamplifier such that the current proportional to V1 is increased from its null value to 1.23 amp. The increase in one servoamplifier current is opposed by the currents in the other three servoamplifiers as shown by voltages V2, V3 and V4 in the chart recording. The chart shows that the output motion of the actuator is 10.0 millivolt which corresponds to 0.0017 inch.

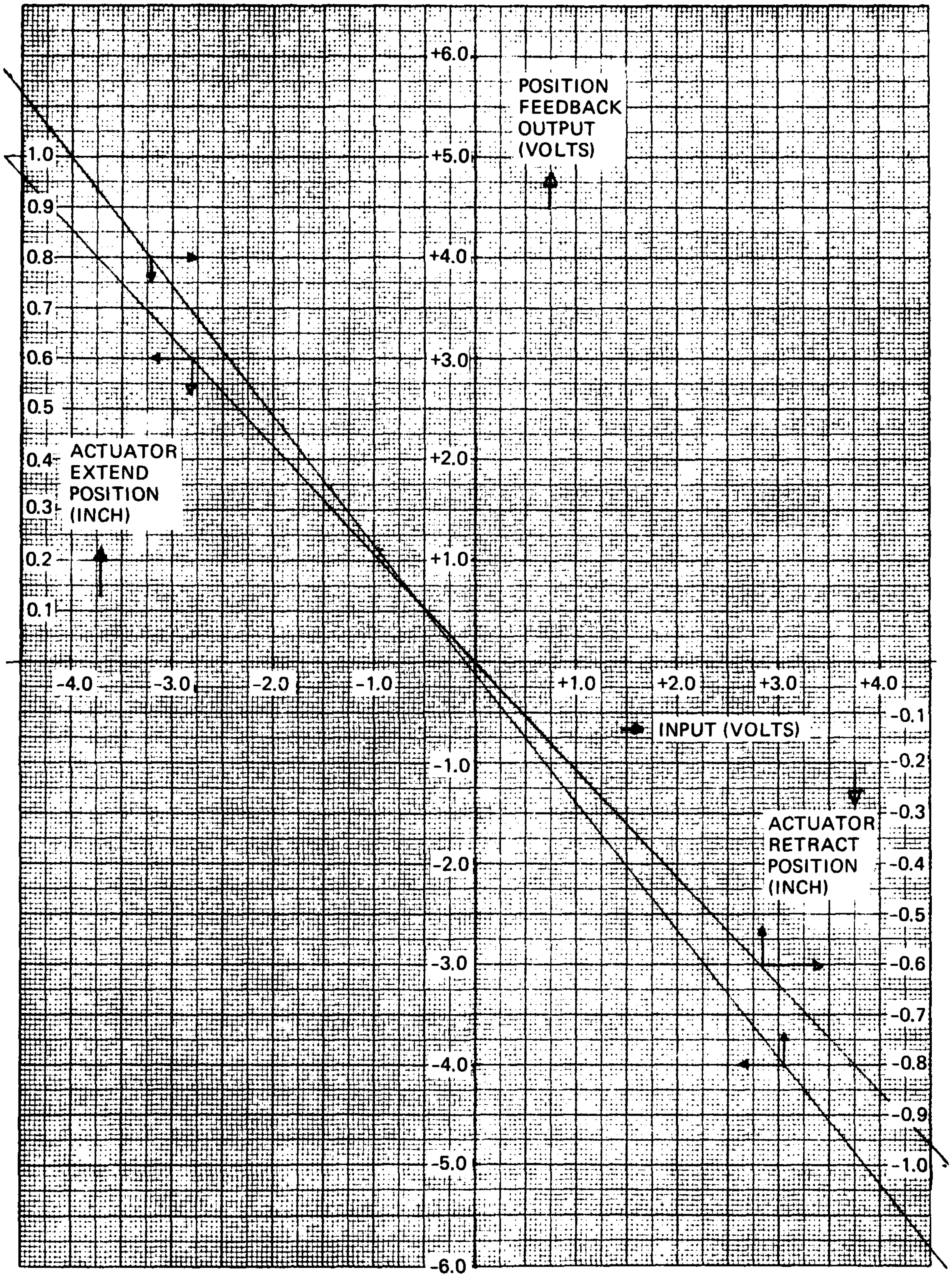


Figure 33. Direct Drive Aileron Actuator Position Gain, Four Coil and Two Coil

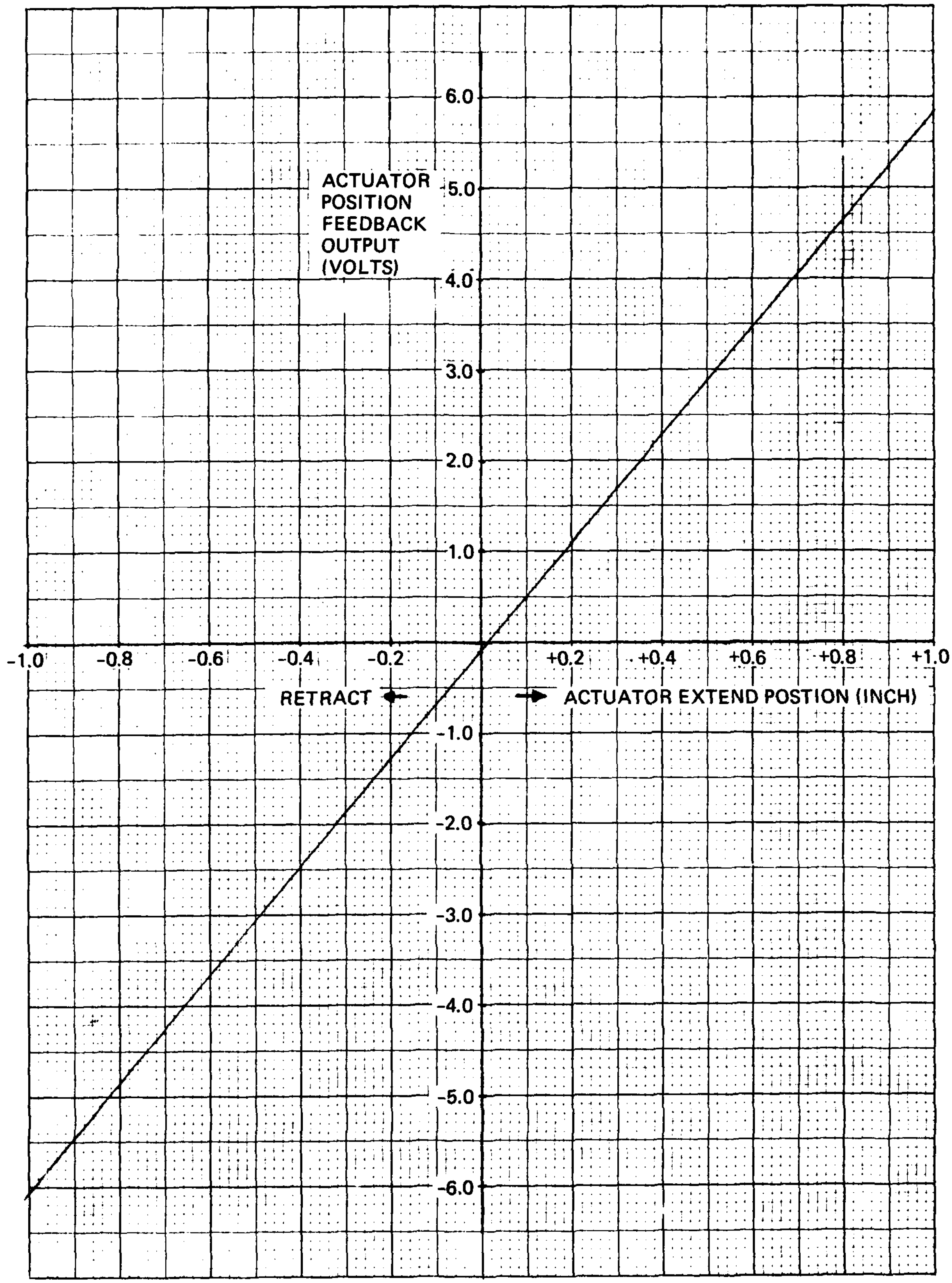


Figure 34. Aileron Actuator Feedback Output Gain

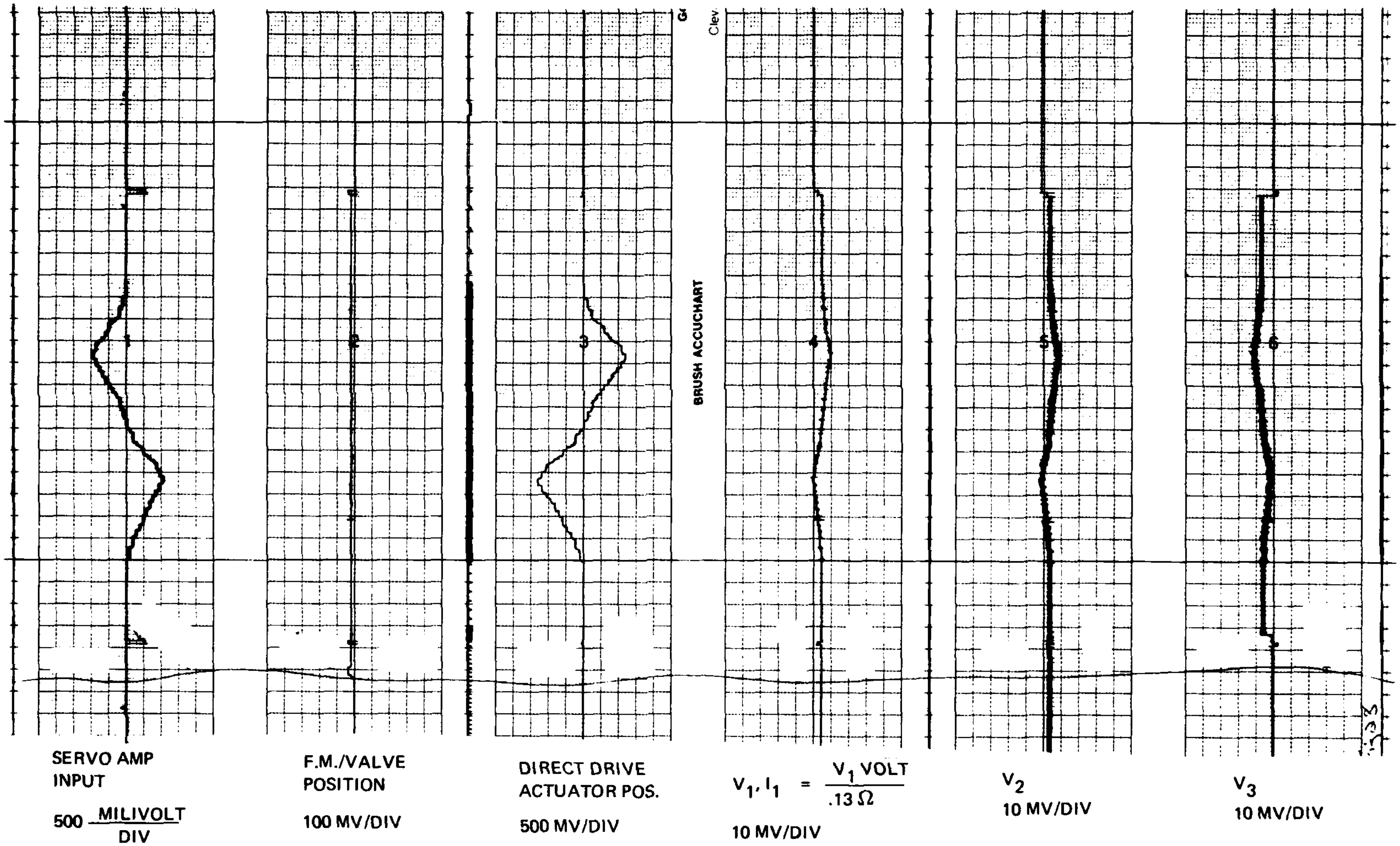


Figure 35. Direct Drive Actuator Position Gain Recording

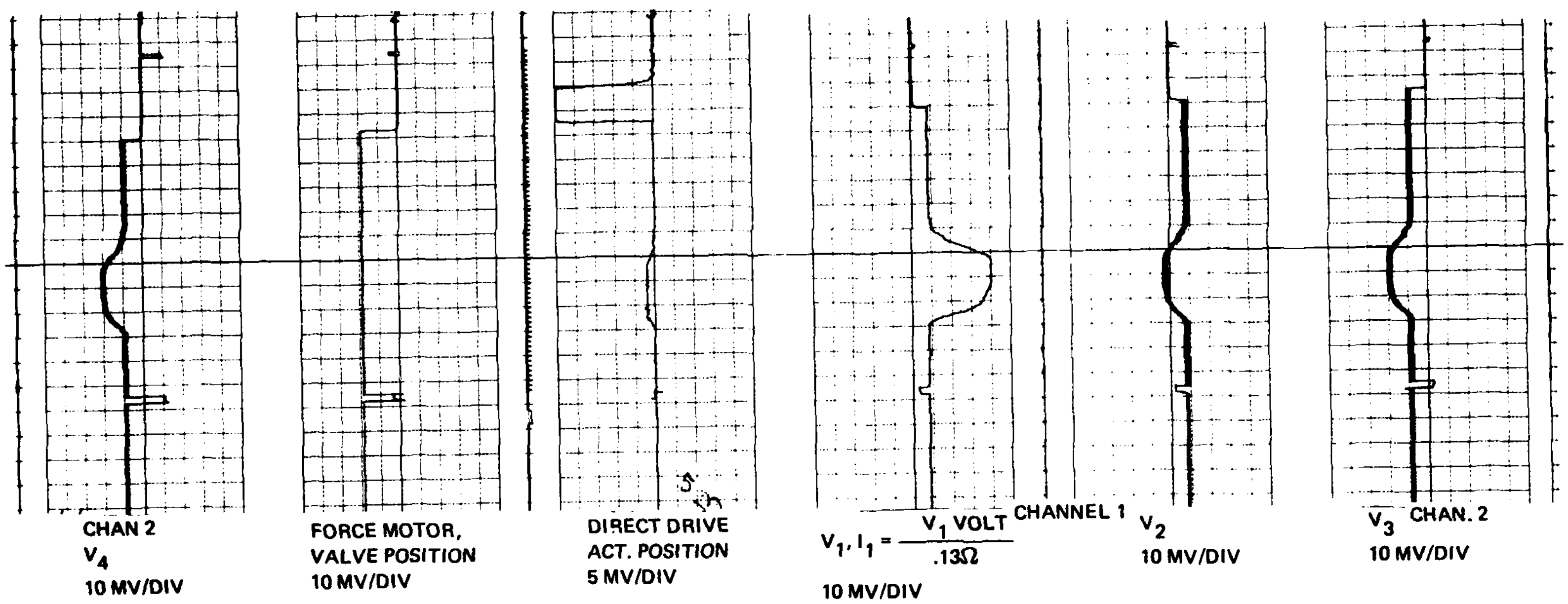


Figure 36 . Simulated Failure Transient for Single Failure Input to V_1 Servoamplifier

The failure correction logic was bypassed during this test since the automatic gain change after a failure had not been implemented in the breadboard electronics. Without the gain change, the residual oscillation due to friction in the valve would have masked any null shift effects after a failure when operating on the remaining channel.

5.4.3 CLOSED LOOP ACTUATOR FREQUENCY RESPONSE AND THRESHOLD TESTS

The minimum dynamic performance as specified in paragraph 4.3.2 of the SOW shall be: amplitude degradation - not more than ± 3db at 5 Hz and 10% stroke; phase shift not more than 90^{o} at 5 Hz.

The frequency response of the breadboard direct drive actuator is shown in Figures 37 and 38. The curves in Figure 37 show the amplitude and phase response of the actuator position output at amplitudes of 10% and 5% of a ±1.1 inch stroke with both electronic channels (4 coils connected) operating. The curves in Figure 38 present the frequency response with only one channel (2 force motor coils connected) of the electronics operating.

From the results presented in these curves, it can be seen that the specified minimum performance is exceeded at both 10% and 5% amplitudes.

Figure 39 presents a chart recording of the frequency response between 1.0 and 9.0 Hz where the largest change in amplitude response occurs. Figure 40 shows the input, force motor position, actuator position and the two signals proportional to coil current in a chart recording of the single channel response between 1.0 and 9.0 Hz.

<u>Threshold</u>

Figure 41 shows a chart recording of the actuator threshold response for dual and single channel operation. From the chart recording it can be seen that the threshold is 1.0 millivolt or less for both cases which corresponds to 0.019% of a ±1.1 inch actuator stroke.

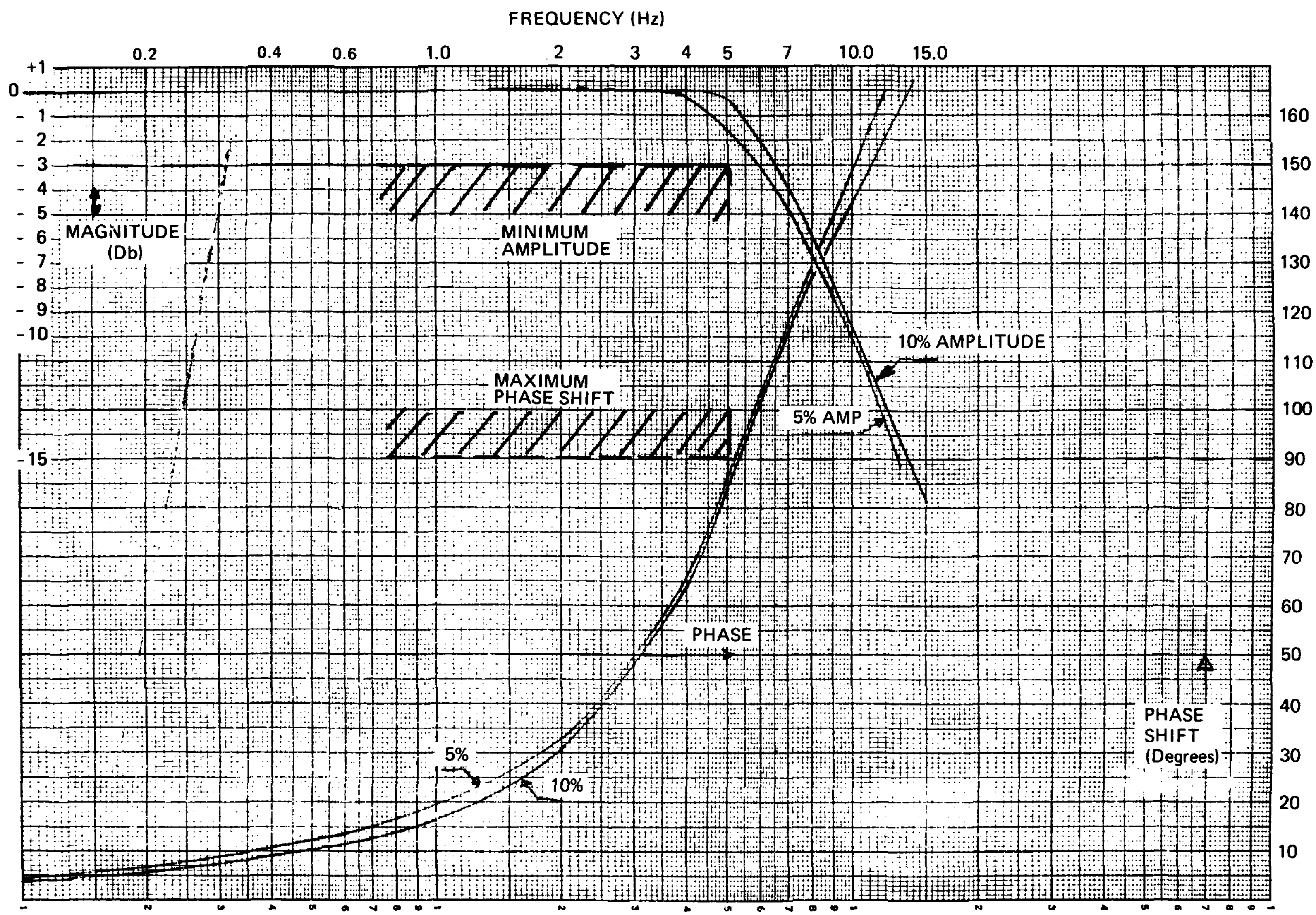


Figure 37. Two Channel Frequency Response, 5% and 10% Amplitude

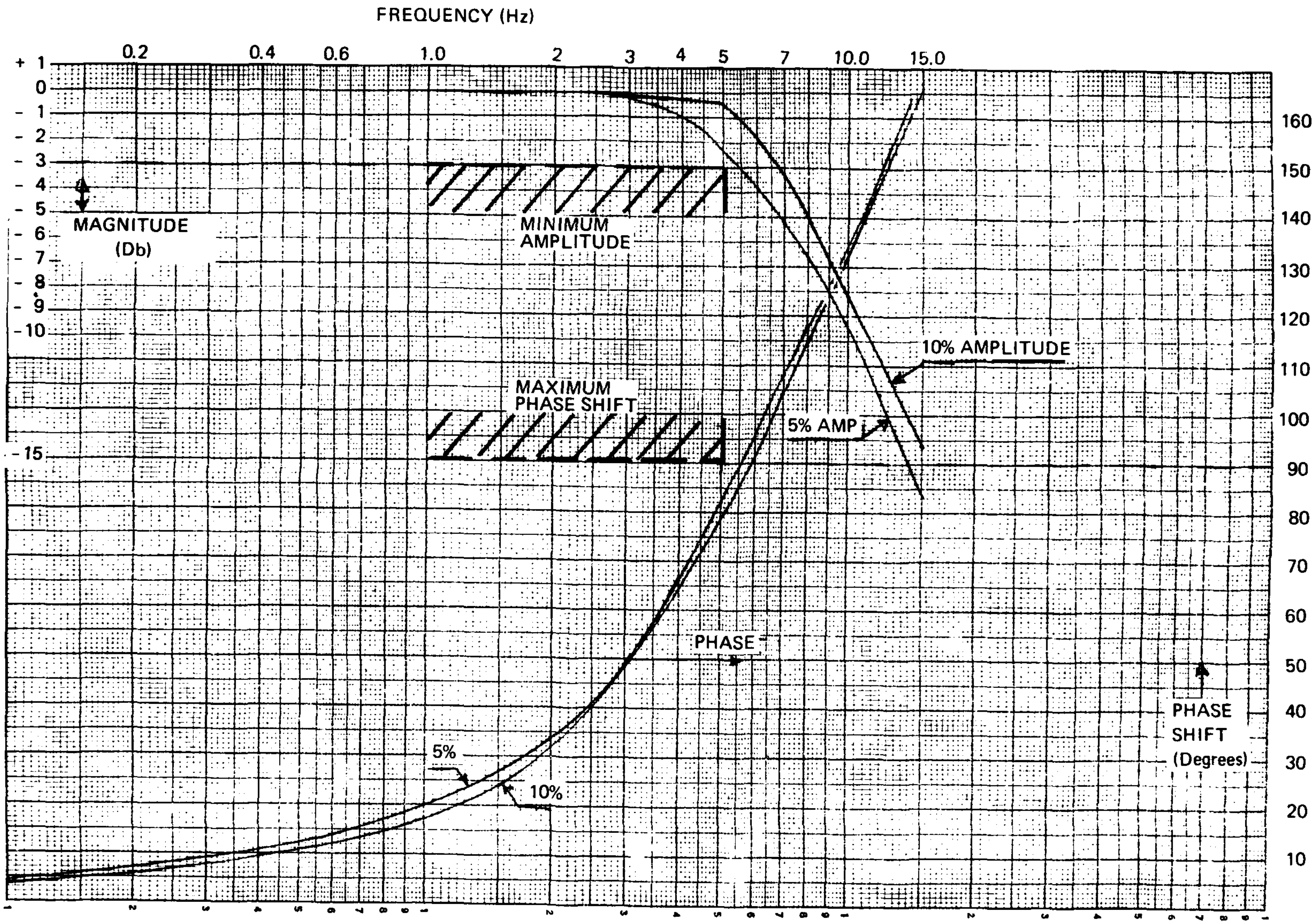


Figure 38. Single Channel Frequency Response, 5% and 10% Amplitude

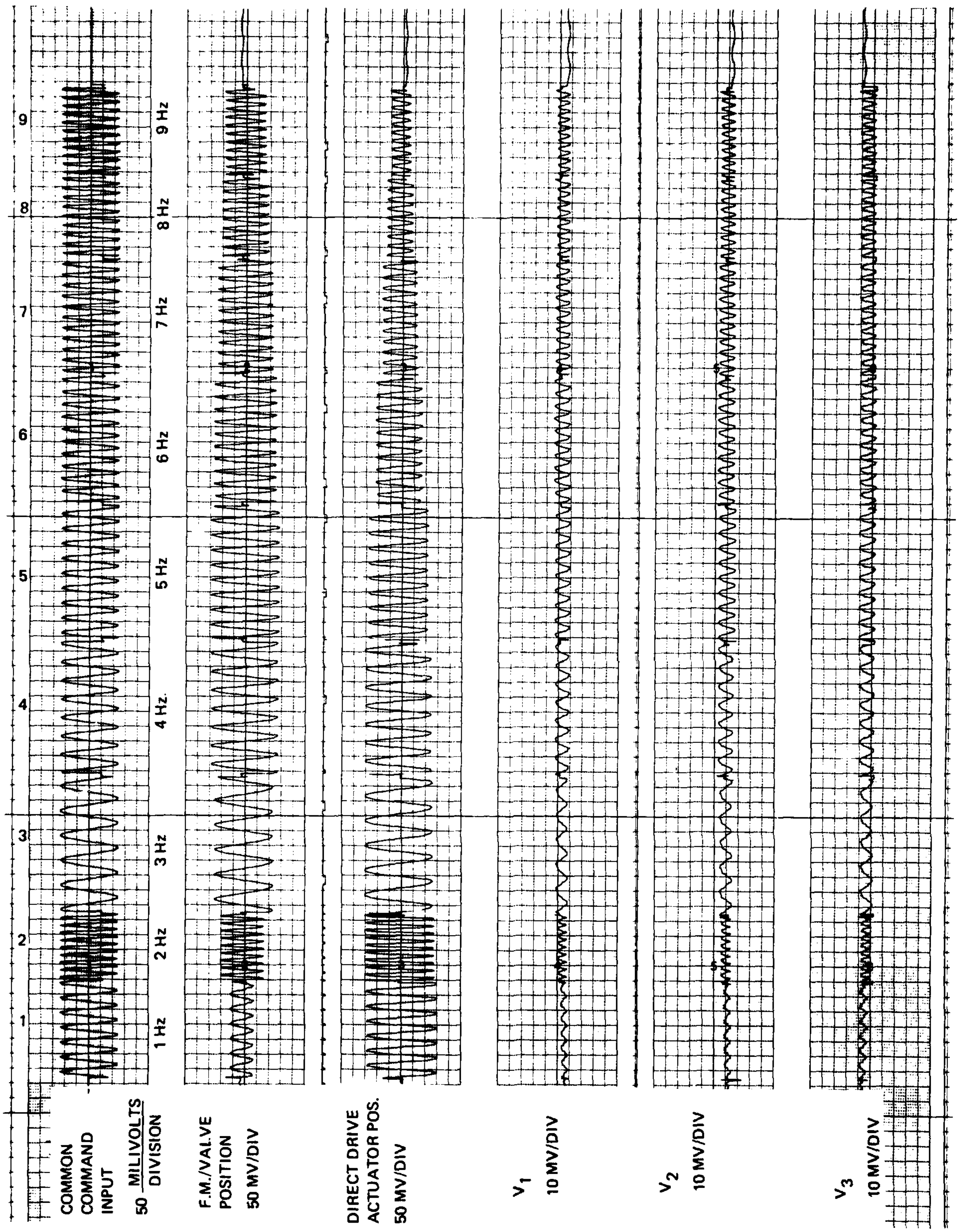


Figure 39. Dual Channel, Four Coil Frequency Response

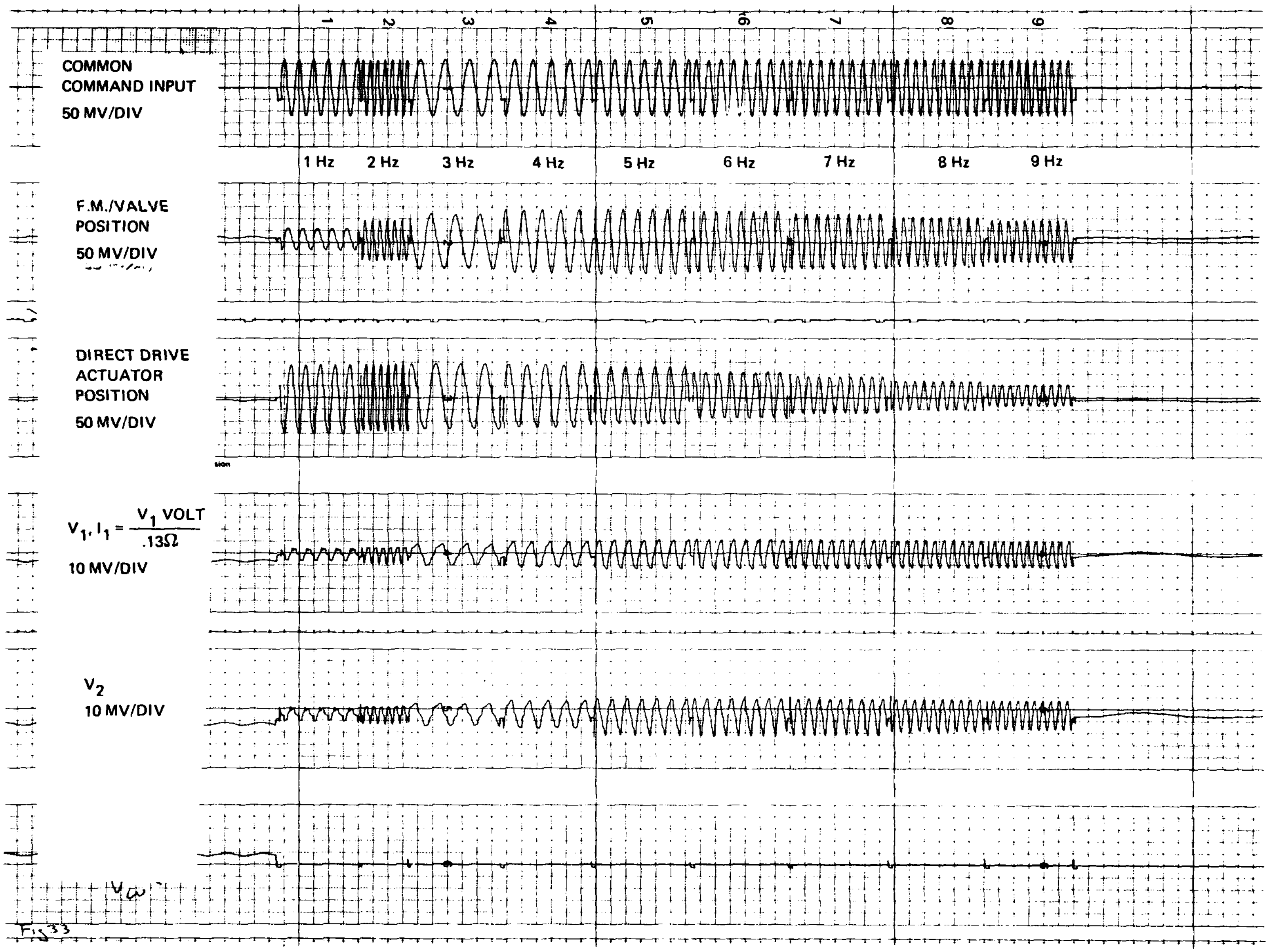


Figure 40. Single Channel, Two Coil Frequency Response

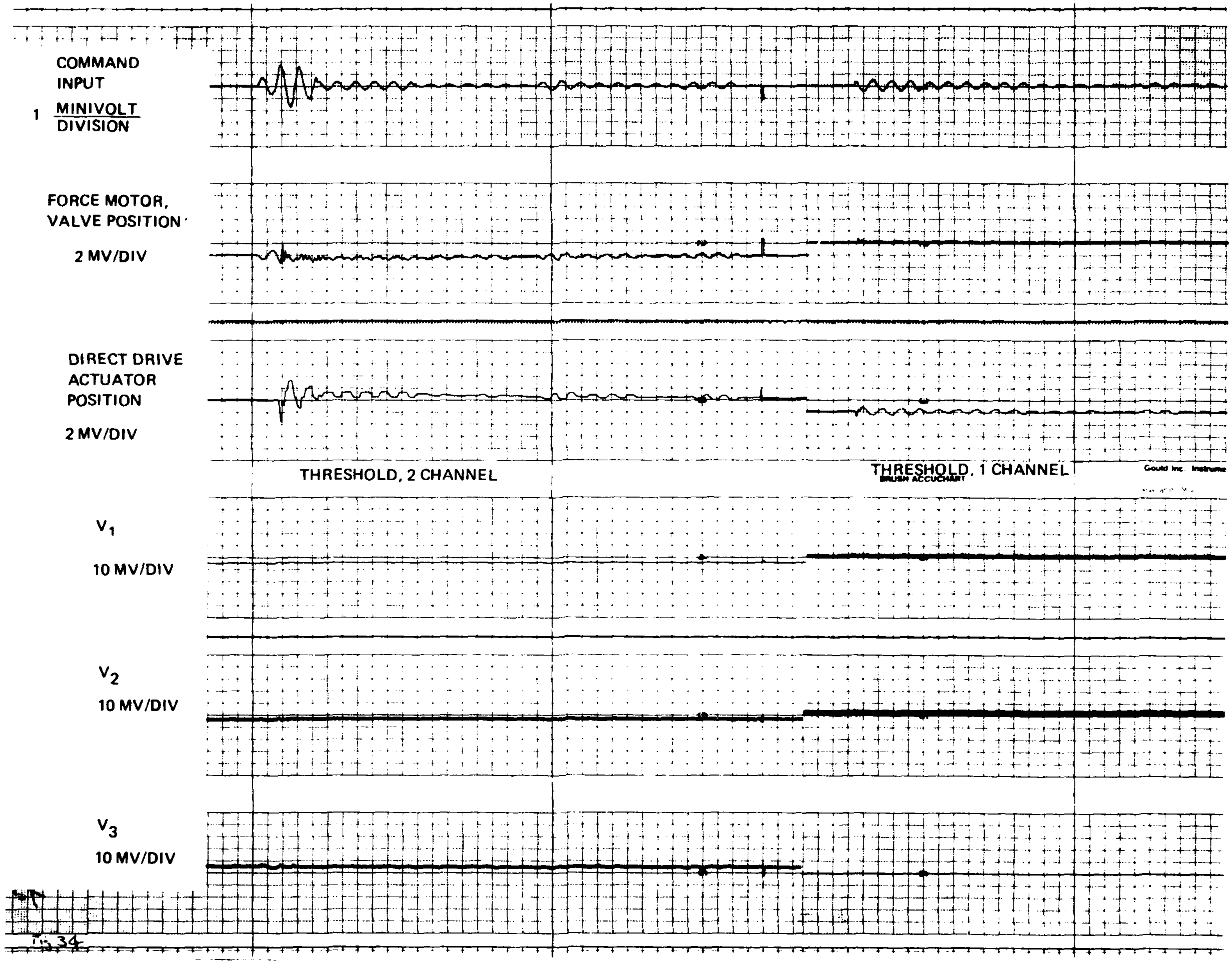


Figure 41. Direct Drive Actuator Threshold, Two Channel and One Channel Operating

5.4.4 OPERATION OF DUAL HYDRAULIC SUPPLIES WITH ONE AT AN OVER TEMPERATURE CONDITION

Tests were conducted on the force motor/control valve with one supply at an overtemperature condition to determine if the control valve had any tendency to stick or bind as the temperature of the oil in one system increased. The tests were conducted with only one control channel (2 coils connected) operational.

Figure 42 presents a temperature vs time plot of the five temperatures measured on the Temperature Chart Recorder during the duration of test with hot oil in the P1, R1 system and cooler oil in the P2, R2 system of the aileron actuator. The T1 and T2 thermocouples were located in the return hydraulic lines from the actuator to the hot and cool oil hydraulic test stands. The T3 and T4 thermocouples were located on the surface of the valve body while T5 was located on the actuator cylinder. The thermocouple locations are shown in Figure 43. Now the temperature plot in Figure 42 shows that the hot oil in the R1 return line reached a temperature of $224^{O}F$ while the cool oil in the R2 return line had a temperature of $113^{O}F$ for a temperature difference of $111^{O}F$ at the conclusion of the test. In normal system operation in the aircraft with P2 oil at $170^{O}F$ then P1 oil would be at $281^{O}F$ for $\Delta T = 111^{O}F$ which is over the Type II maximum oil temperature of $275^{O}F$.

The plot in Figure 42 also indicates the times and temperature differences when the input-output (X-Y) recordings and the chart recordings of input, output and the two force motor currents were taken.

The X-Y plots shown in Figure 44 at the start of the test and at temperature differences at 22^{O}, 80^{O}, 101^{O} and $111^{O}F$ do not show any large increase in hysteresis that would indicate sticking or binding of the valve spool as the force motor/control valve position was varied from 0.060" extend to 0.060" retract. A small variation at null is shown by the X-Y recordings at $\Delta T = 100^{O}$ and $111^{O}F$. The chart recording in Figure 45 shows some differences in the current as pressure and temperature increase. The current peak is smallest at the start when the P1 and P2 pressures were zero and only the centering spring and valve friction forces had to be overcome. At $\Delta T = 22^{O}F$ and P1 = P2 = 1000 psi the current peak is higher due to increased friction caused primarily by the increase in pressure which increases the squeeze on the return pressure to atmospheric pressure O-ring seals on the spool valve. After the data was taken at $\Delta T = 22^{O}F$, the hot oil hydraulic system pressure was increased to 3000 psi and the cooling water to the heat exchanger on the test stand shut off so that the hot oil temperature would increase more rapidly. Thus the current peak at $\Delta T = 80^{O}F$ also reflects this increase

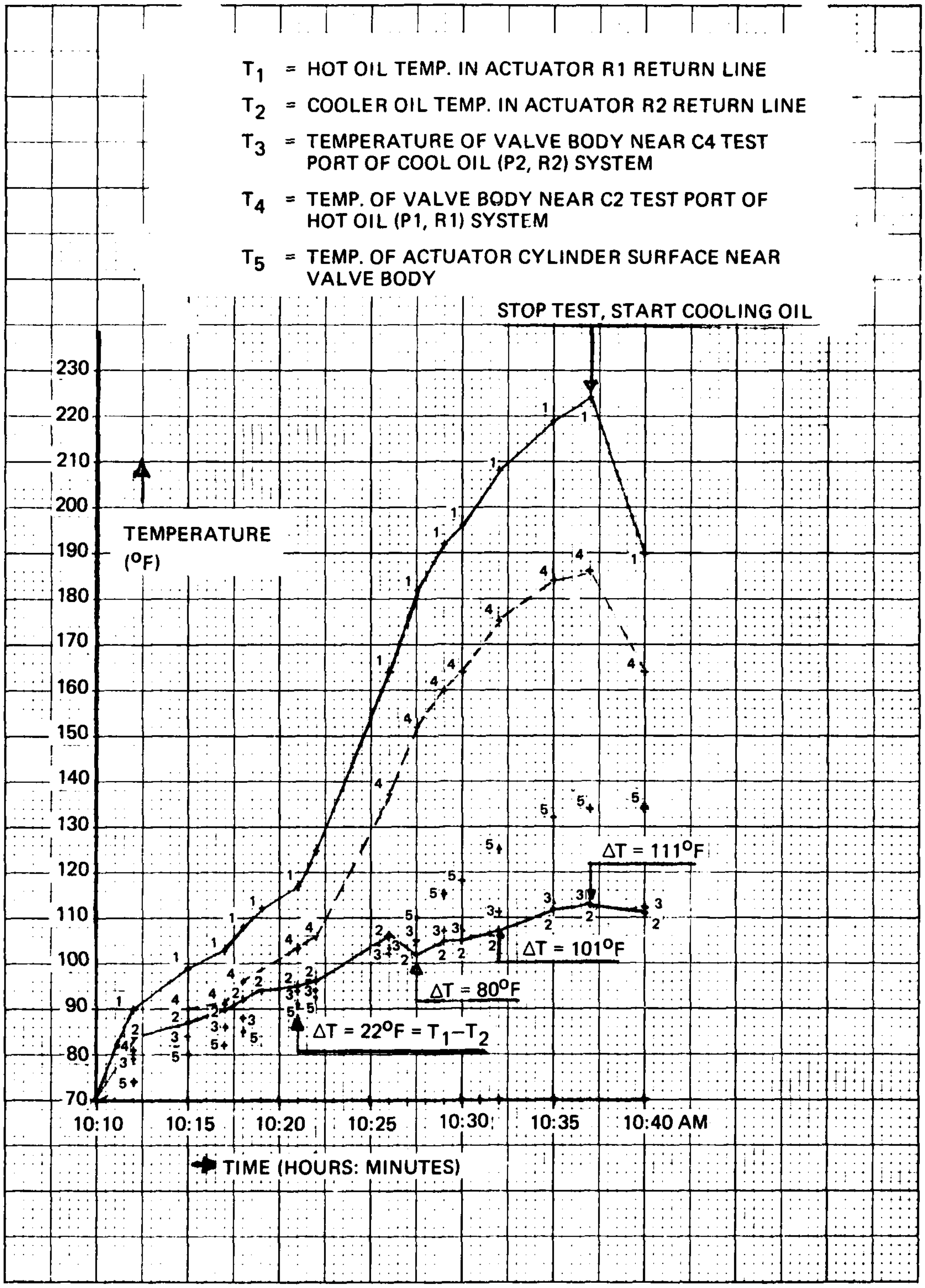


Figure 42. Temperature vs Time With One Hydraulic System at an Overtemperature Condition

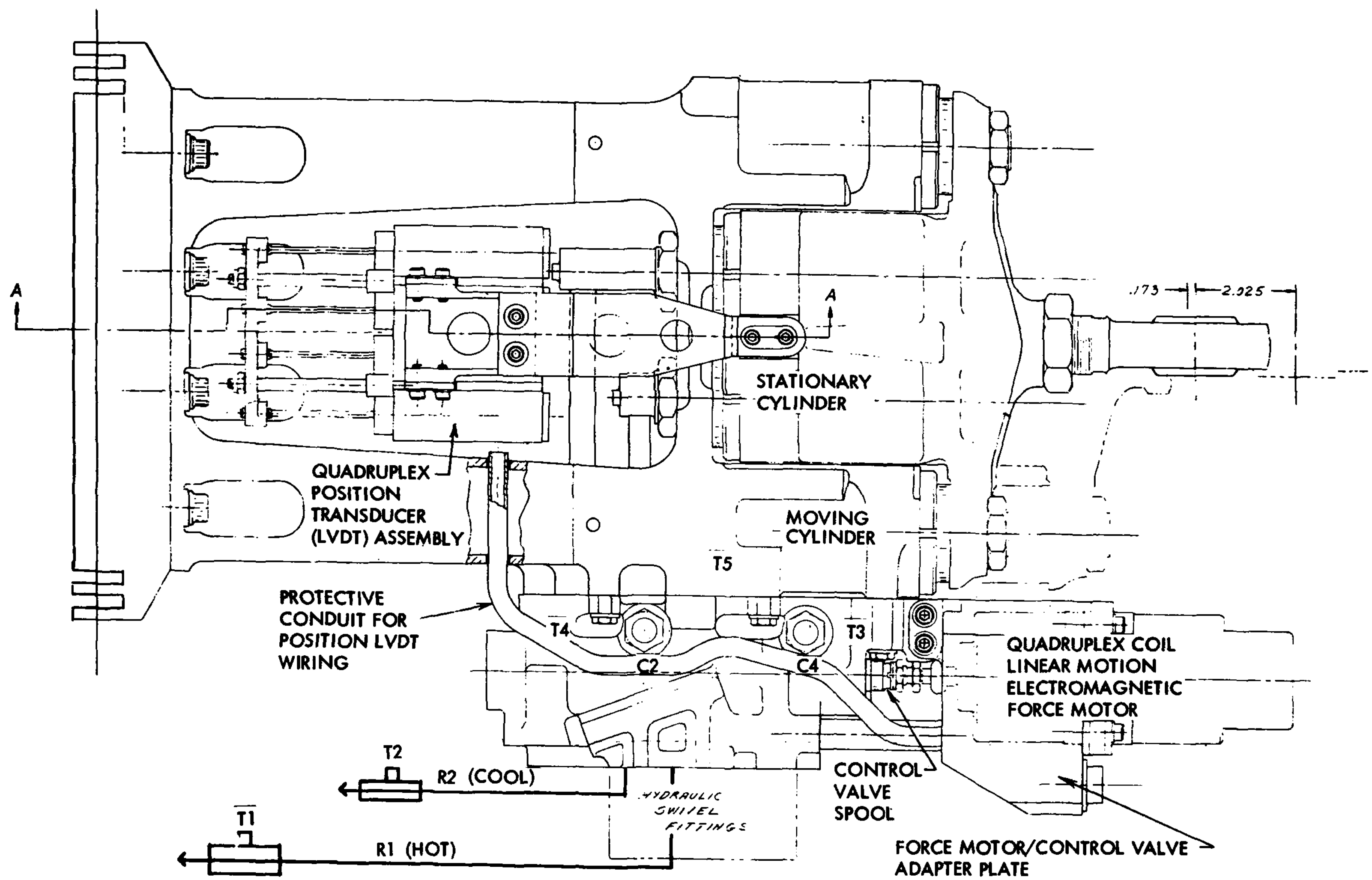


Figure 43. Thermocouple Locations, Overtemperature Oil Test

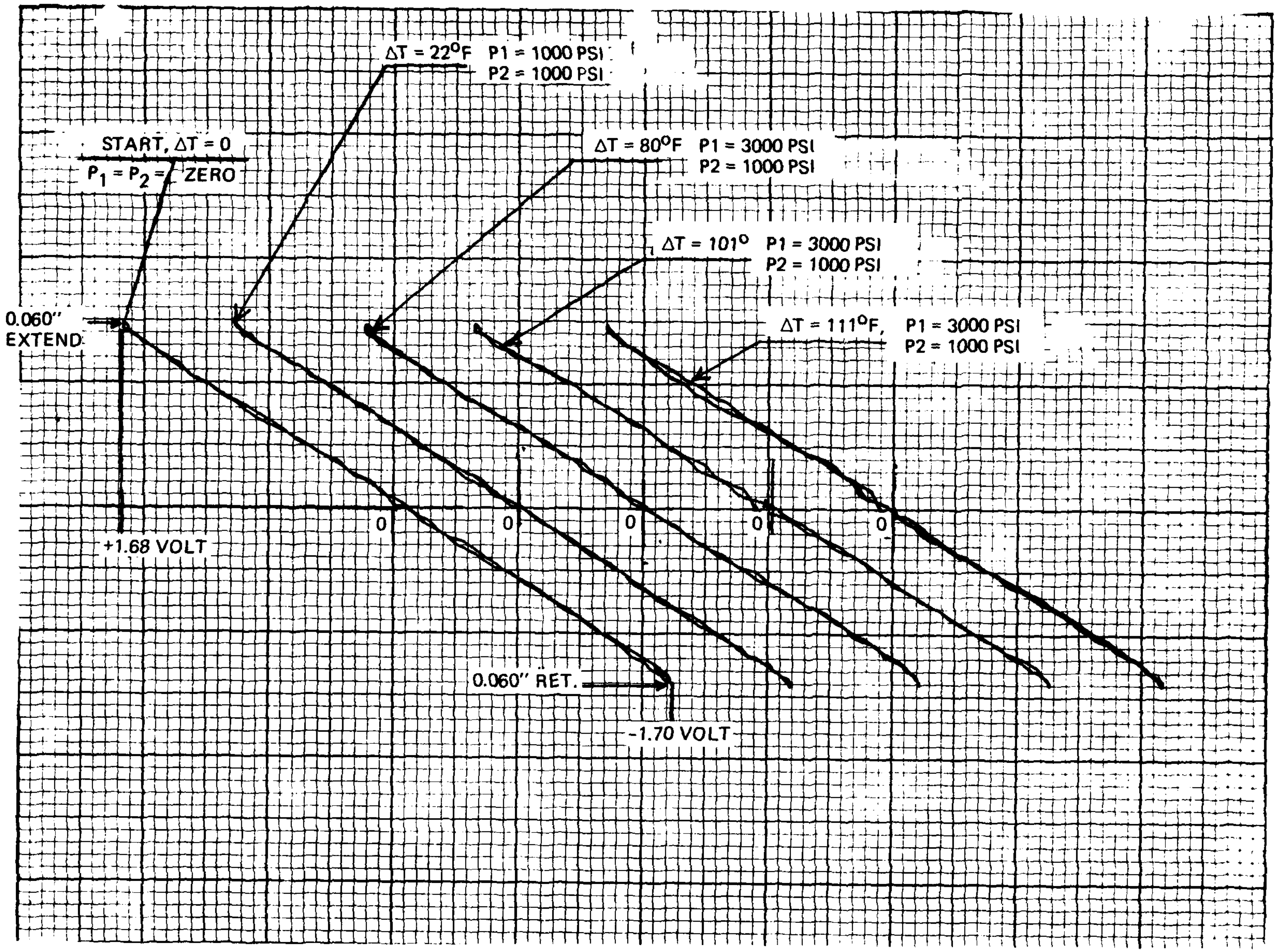


Figure 44. Force Motor/Valve Position vs Input to Servoamplifier, Overtemperature Oil Test

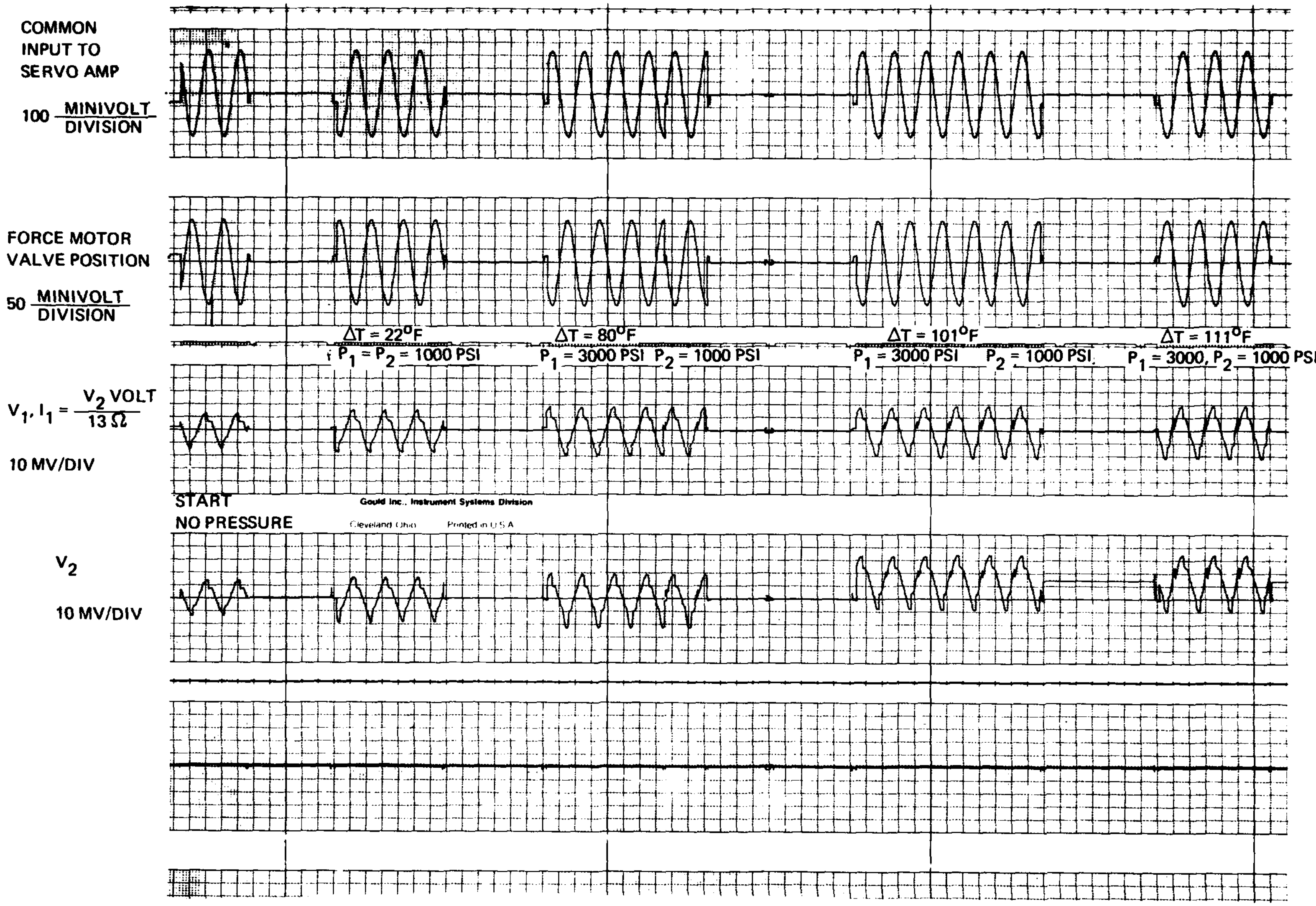


Figure 45. Force Motor Position, Current and Input During Hot Oil Test

in supply and return pressure due to the higher flow through this section of the control valve. The current peak at $\Delta T = 101^{o}F$ and $111^{o}F$ is only about 1/2 of a division higher on the chart recording compared to $\Delta T = 80^{o}F$. At $\Delta T = 101^{o}$ and $111^{o}F$, the chart recording of valve position also shows a small variation while the current trace has a "Glitch" as the valve position is going through null from a retract position to an extend position. This position variation and "glitch" in the current trace is not evident when the force motor/valve position is going through null from an extend position to a retract position. This might be caused by difference in expansion of the housing and the other spring which causes a different preload or centering force in one direction. What ever the cause, the effect on force motor/control valve performance during this test is very small.

In conclusion it can be stated that the force motor/control valve performance was satisfactory and no evidence of sticking or binding in the control valve was observed during this test when the return oil temperature achieved a maximum difference of $111^{o}F$.

BREADBOARD TEST SUMMARY

All components of the Direct Drive Actuation System were breadboarded and evaluated.

FORCE MOTOR

The objective of 80 pounds force at center stroke was met with a current of 1.12 amps per coil. The coil resistance average 5.2 ohms resulted in a power input of 6.5 watts per coil or 26 watts total for 80 pounds.

ELECTRONICS

Several circuit changes were made as a result of the limit cycle problem resulting from high valve friction.

The force motor position loop gain was increased and the second channel was put in an "on-line" configuration by a gain reduction. The low gain reduces the force fight between channels reducing power dissipated and improving small amplitude performance. A low amplitude sinusoidal dither signal was also added to further reduce the effect of valve friction.

ACTUATOR AND SYSTEM

Closed loop system tests performed included:

1) Gain and tracking
2) Failure transients
3) Frequency response
4) Threshold
5) Differential oil temperature

Specification requirements and design objectives were met and no design deficiencies were noted.

SECTION III

FLIGHT TEST EQUIPMENT

VALVE DRIVER

DESIGN CHANGES

The breadboard force motor was a prototype model in that no performance or form factor deviations were taken. Breadboard testing demonstrated adequate force and bandwidth performance. The design changes listed for the flyable equipment were therefore producibility/cost changes.

- The magnet assembly was redesigned to reduce the manufacturing cost and optimize the magnetics.
- Secondary air gap (magnet to armature) was made larger to minimize the radial load on the bearings that can exist if the armature is not centered.
- Elastomeric secondary springs were designed to replace the berylium copper star springs.
- All silicon iron parts were electroless nickel plated.
- Coil space was slightly enlarged and more wire turns were added to achieve the original design goal of 1 amp per coil at 80 lb.

The final force motor configuration is shown in Figure 46. A photograph of the completed torque motor and a disassembled unit is included as Figure 47.

The dimensions of the unit are shown in the outline drawing which is included as Figure 48.

The force motor weighs 7.2 pounds.

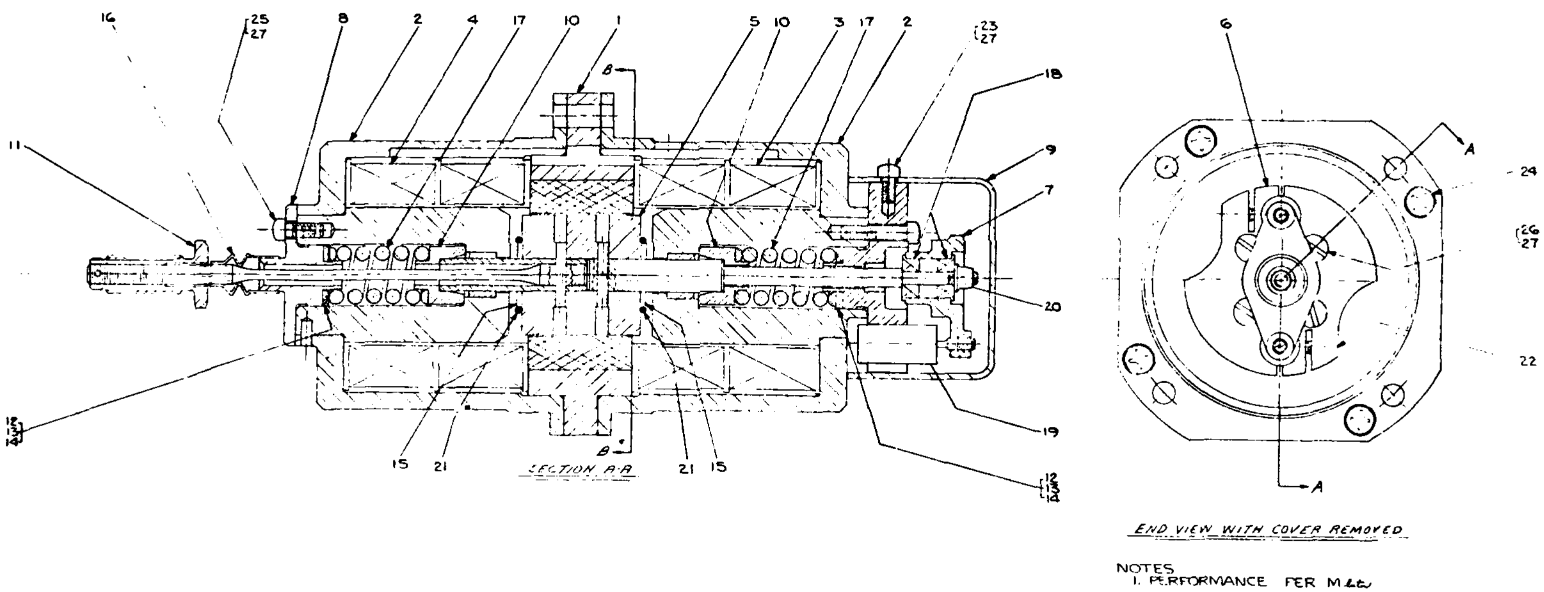
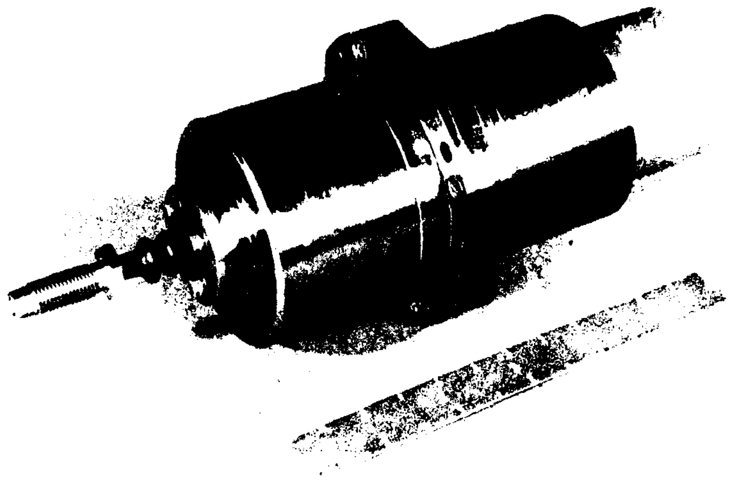
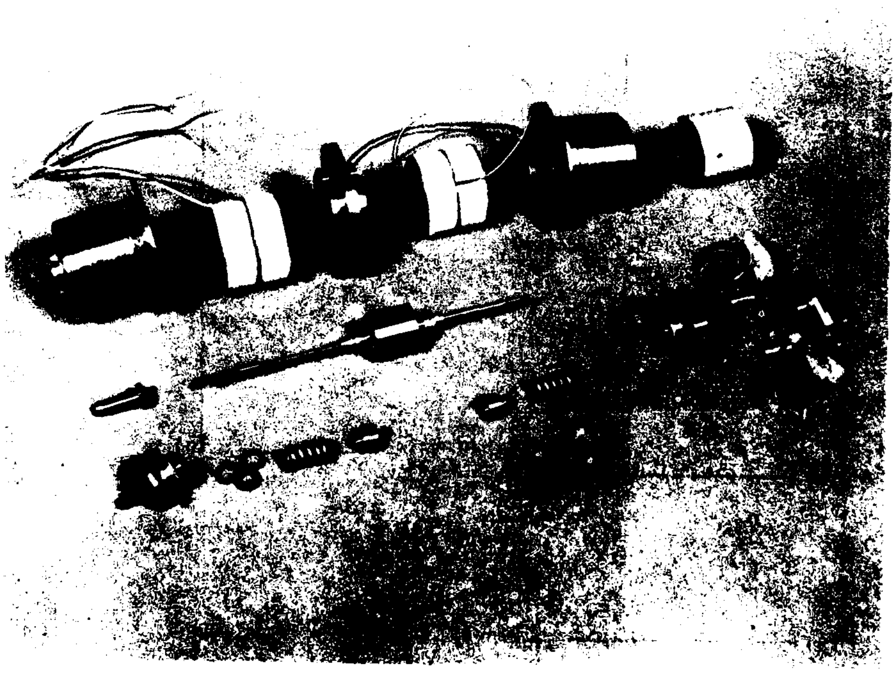


Figure 46. Final Force Motor Configuration



Assembled 25321



Disassembled

Figure 47. Force Motor 25322

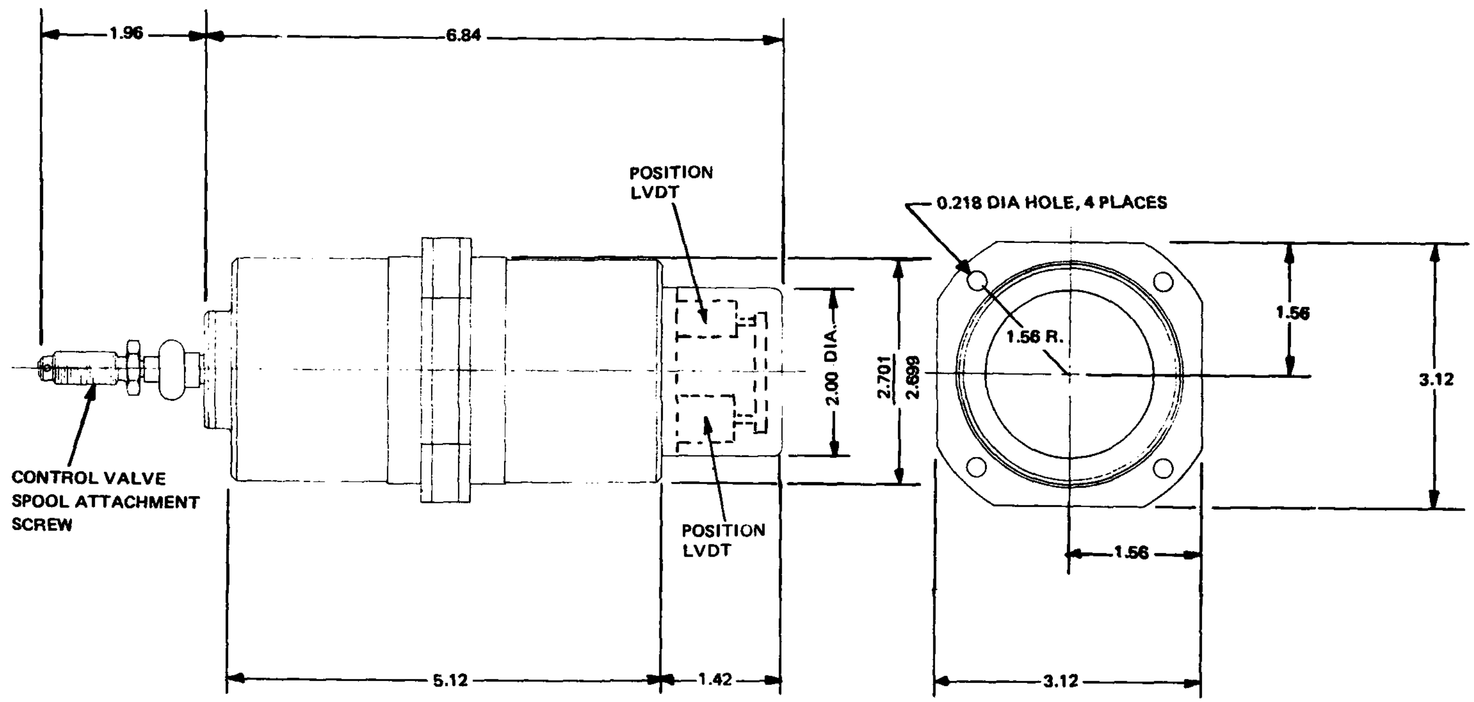


Figure 48. Linear Motion Bi-Directional Force Motor Outline Drawing

TEST DATA

The force motor open loop output capability over the limits of stroke was measured for the flyable model, see Figure 49. The new design correlates very closely with the breadboard except for a slightly increased force gain due to the increase in coil turns. The current to produce 80 pounds at center stroke is now 4 amperes; the force gradient is 20 pounds per ampere.

No other differences in performance between the breadboard and the flyable force motors were discovered in the testing.

Figure 50 is a plot of output force generated at center stroke as a function of total current with 4 coils and with 2 coils connected. The force gradient is 20.0 pounds per amp driving 4 coils and 18.6 driving 2 coils.

The spring constant of the armature suspension is the slope of the constant force lines of Figure 46 and is approximately 267 pounds/inch.

The closed loop force motor characteristics of interest are stiffness, threshold and frequency response.

The closed loop static stiffness of the force motor could not be measured accurately in the laboratory because the deflections were less than 0.001 inches and difficult to measure conveniently. Figure 51 is a block diagram of the final gains associated with the inner loop. The calculated stiffness is 1.2×10^{-5} inches/pound which roughly corresponded to test results obtained with a 50 pound external load.

The frequency response of the motor is shown in Figure 52 with the low frequency magnitude at 50% of full scale output position. The 90 degree phase point occurs at 40 Hz.

Figure 53 indicates the threshold of the force motor position loop. A low frequency sinusoidal signal was slowly increased in amplitude until motion was observed at the demodulated position transducer output. Approximately 3 mv is required where 1.17 volts commands full motion or 0.25% of full scale.

A distinction must be made between "four coil" and "two channel" operation. For evaluation purposes, four coil operation was a parallel connection of the 4 coils and equal currents in each. Two channel operation, however, does not drive the four coils with equal currents because the on-line redundancy management concept reduces the second channel gain. Hence, tests made with the system electronics are identified as "single channel" or "two channel" data. The second channel gain is increased to full value if channel one is shut down or if the channel 1 current rises to a 0.5 amp level.

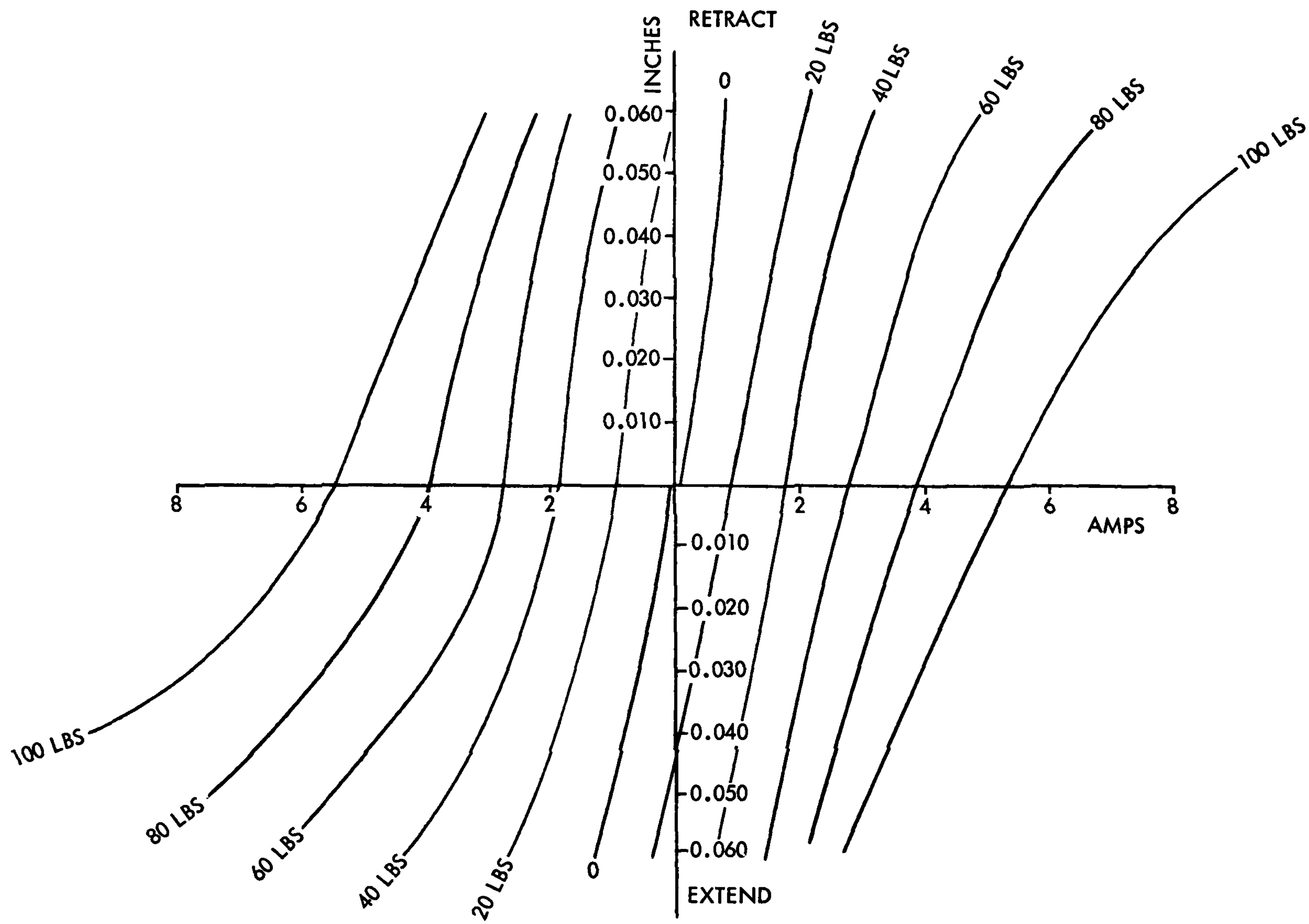


Figure 49. Force Motor Open Loop Output Capability Over Stroke Limits

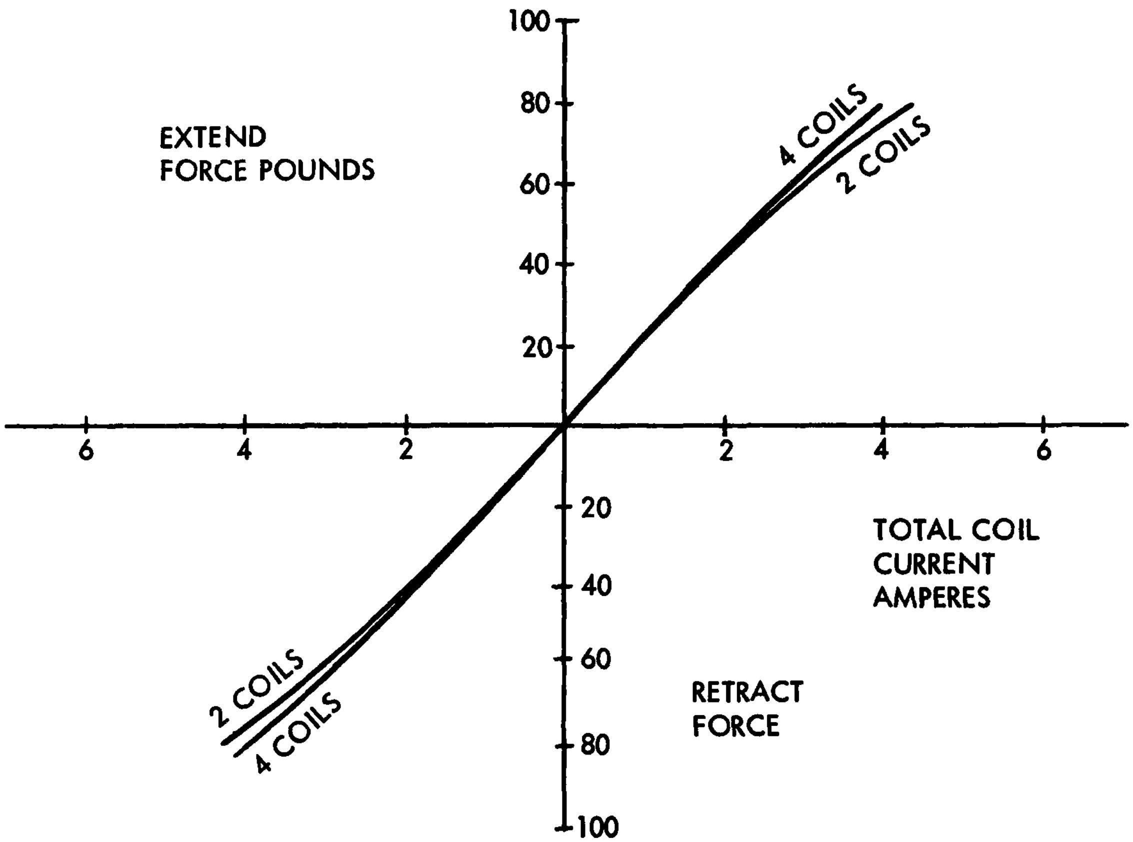


Figure 50. Force Motor Output at Center Stroke, Four Coils and Two Coils

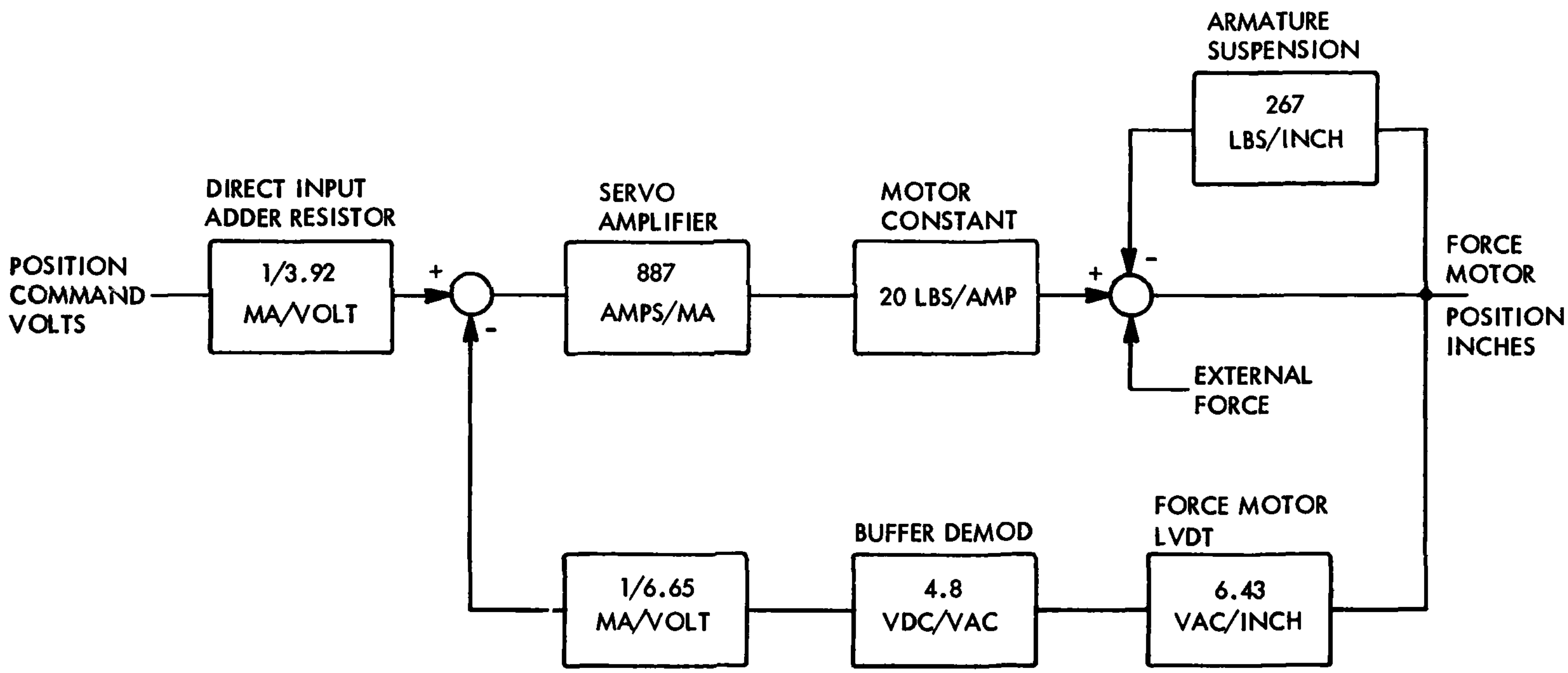


Figure 51. Force Motor Loop Gains

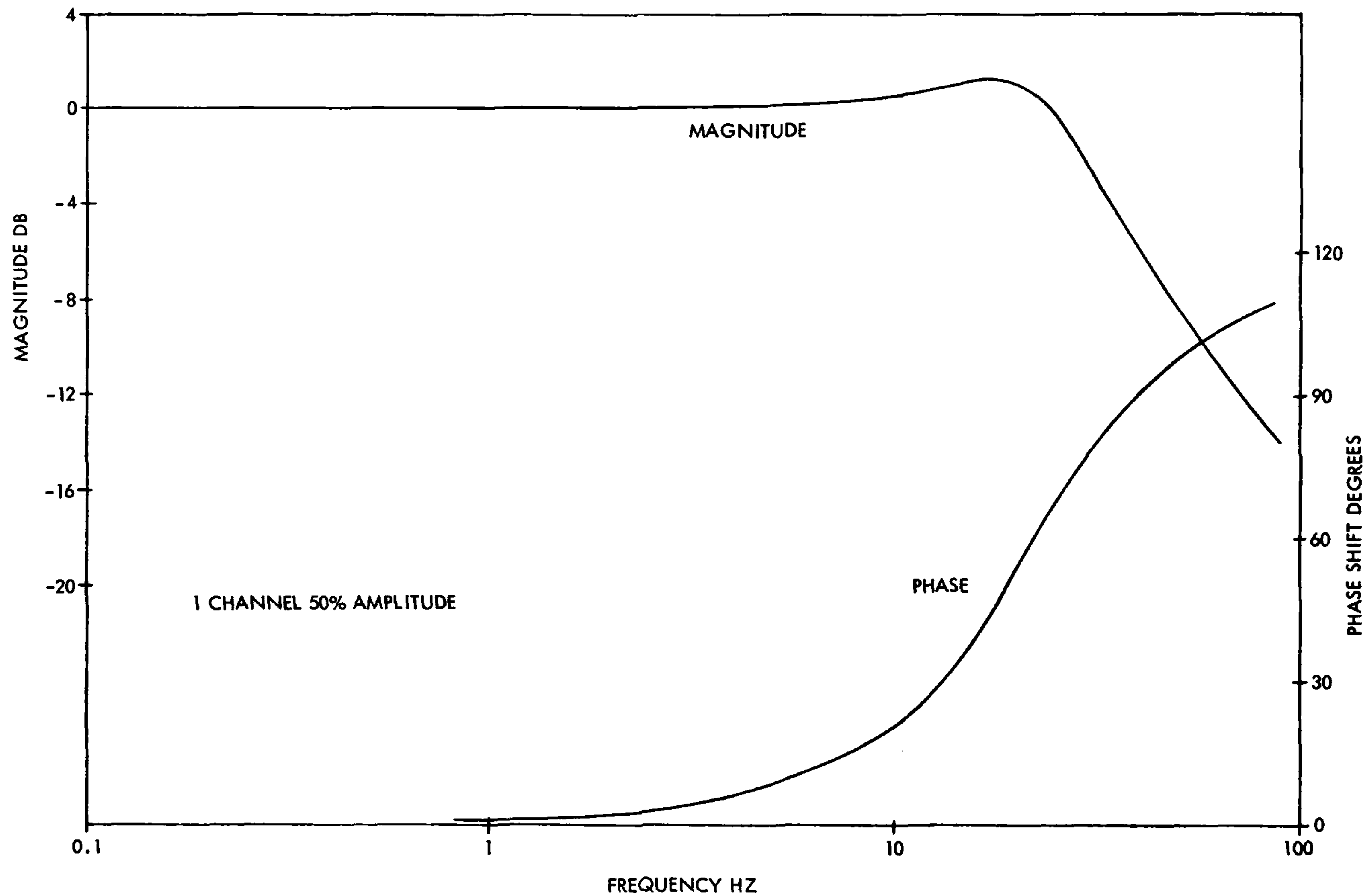


Figure 52. Frequency Response Flightworthy Force Motor

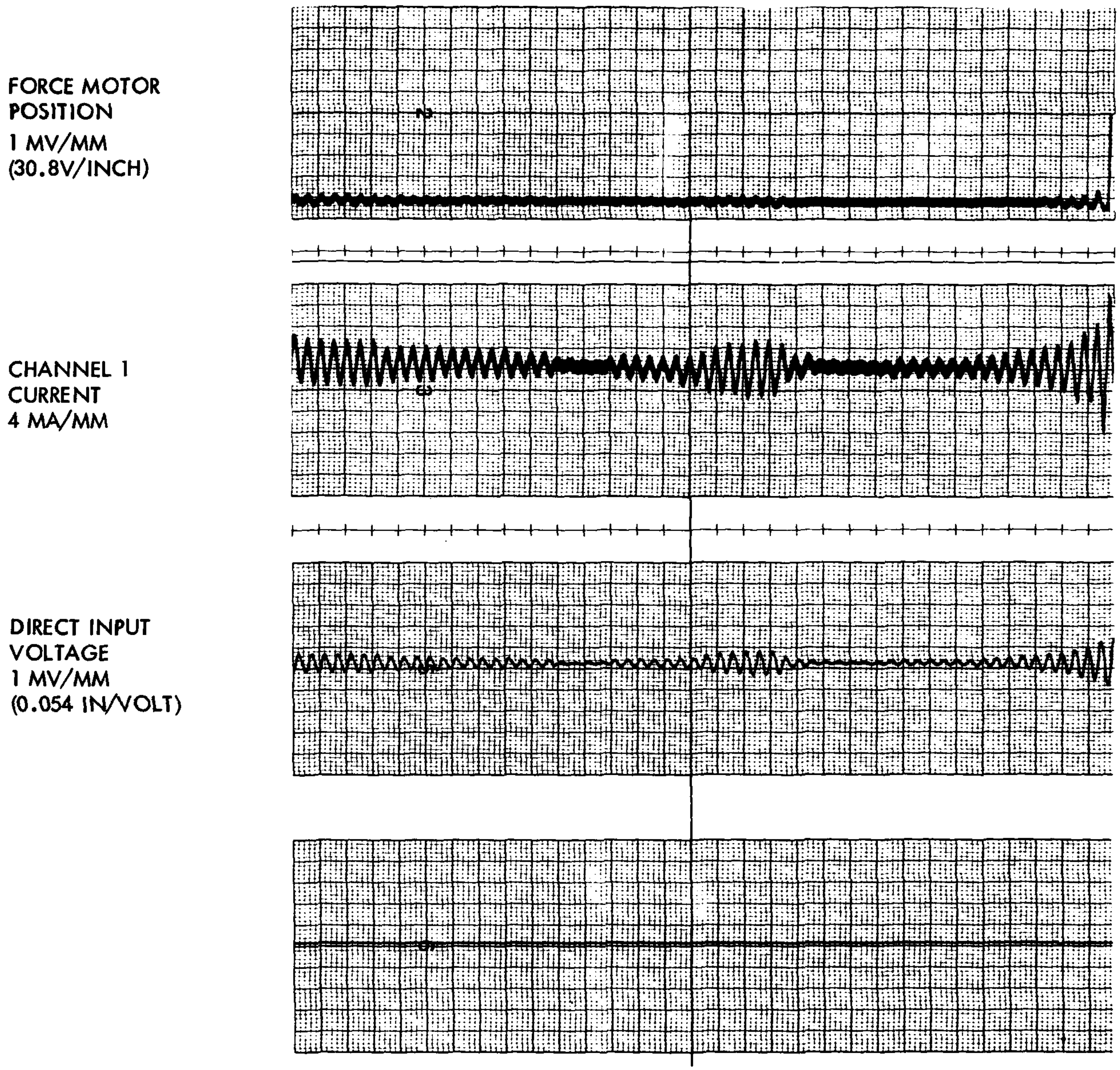


Figure 53. Force Motor Threshold Flightworthy Equipment

The closed loop characteristics of the flightworthy force motor do not differ from those of the breadboard. The difference in system operation results from the change in system configuration to the on-line approach which results in fewer differences in two channel and one channel operation.

ELECTRONICS

FUNCTIONAL DESCRIPTION

The complete electrical schematic is included as Figures 54 and 55. The electronics consist of the following functions: identical command and model force motor drive circuits, fail detection circuits and power supply circuits.

The force motor drive circuits provide input buffering of control stick force motor position and actuator position LVDT's mechanized with differential amplifiers. This configuration permits common mode rejection of the buffer operational amplifiers to attenuate EMI and noise on the input signal wires. Each buffer output is synchronously, full wave demodulated and summed, after appropriate filtering, into the command or model summing amplifier. The error signal at the output of the summing amplifier is averaged and amplified in the servoamplifiers to drive the force motor. The servoamplifier consists of a linear op. amp. and an output state that is a bipolar darlington arrangement. Motor current feedback is used for gain control. Use of motor current feedback minimizes winding inductance frequency response effects and provides a constant gain unaffected by load resistance changes. The gain of the current stage is 6823 ma/ma. Including the input resistor, R43, the gain is 3.41 amp/volt in the high gain condition. In order to implement a low gain for "on-line" operation, an active negative feedback employing AR4 is used. The low gain state is caused when Q6 is off allowing the active feedback path to parallel R80 and reduce the gain to 88 ma/volt. Q6 is always turned on in channel 1.

Should the loop error increase such that the amplifier output reaches ±0.5 amps, the same active feedback is limited by diodes CR7, CR8, CR9 and CR10, and the gain reverts to full value. In the event of valve contamination or any condition requiring high force, the full drive power of all four amplifiers is available to reduce the loop error.

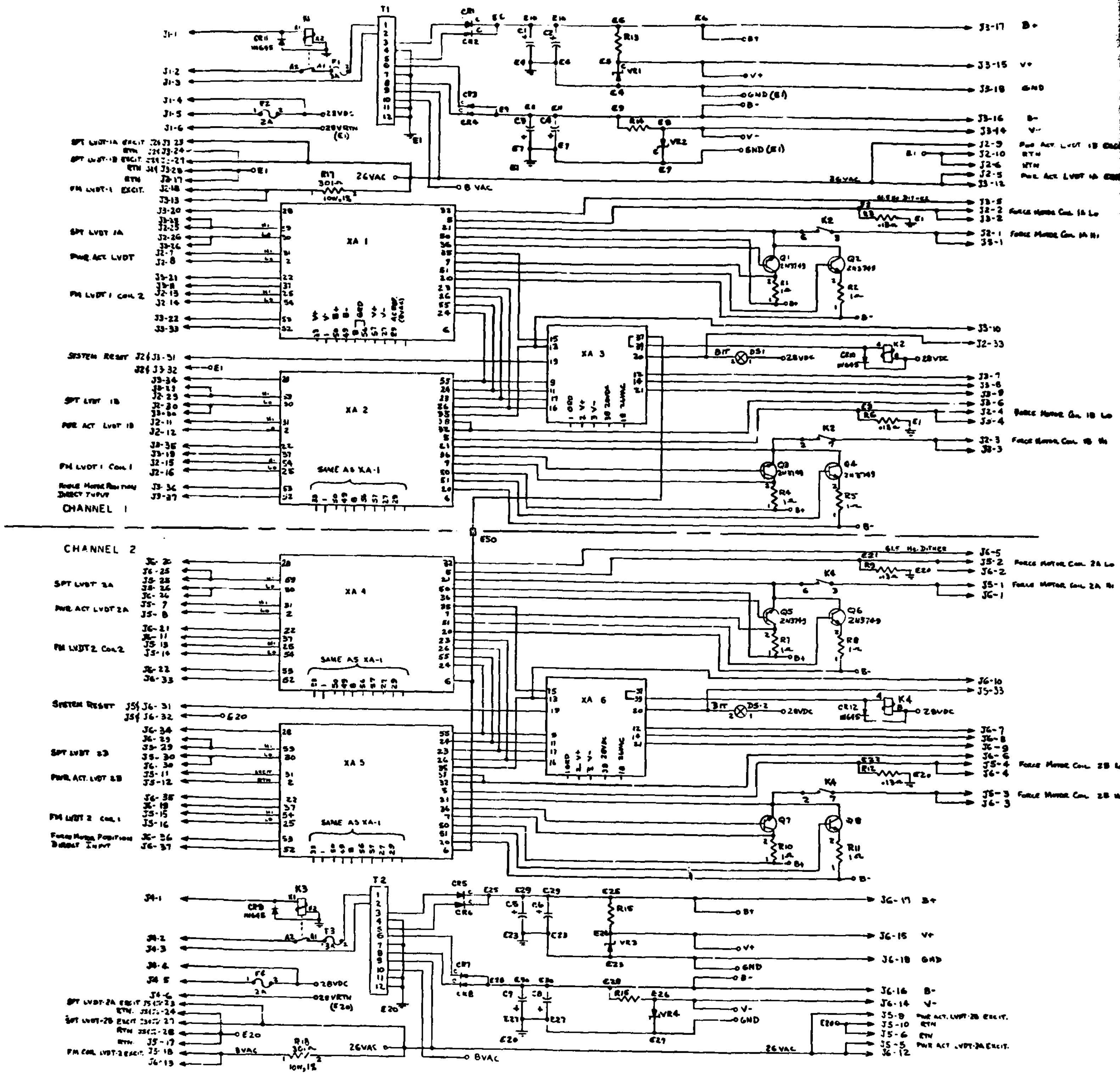
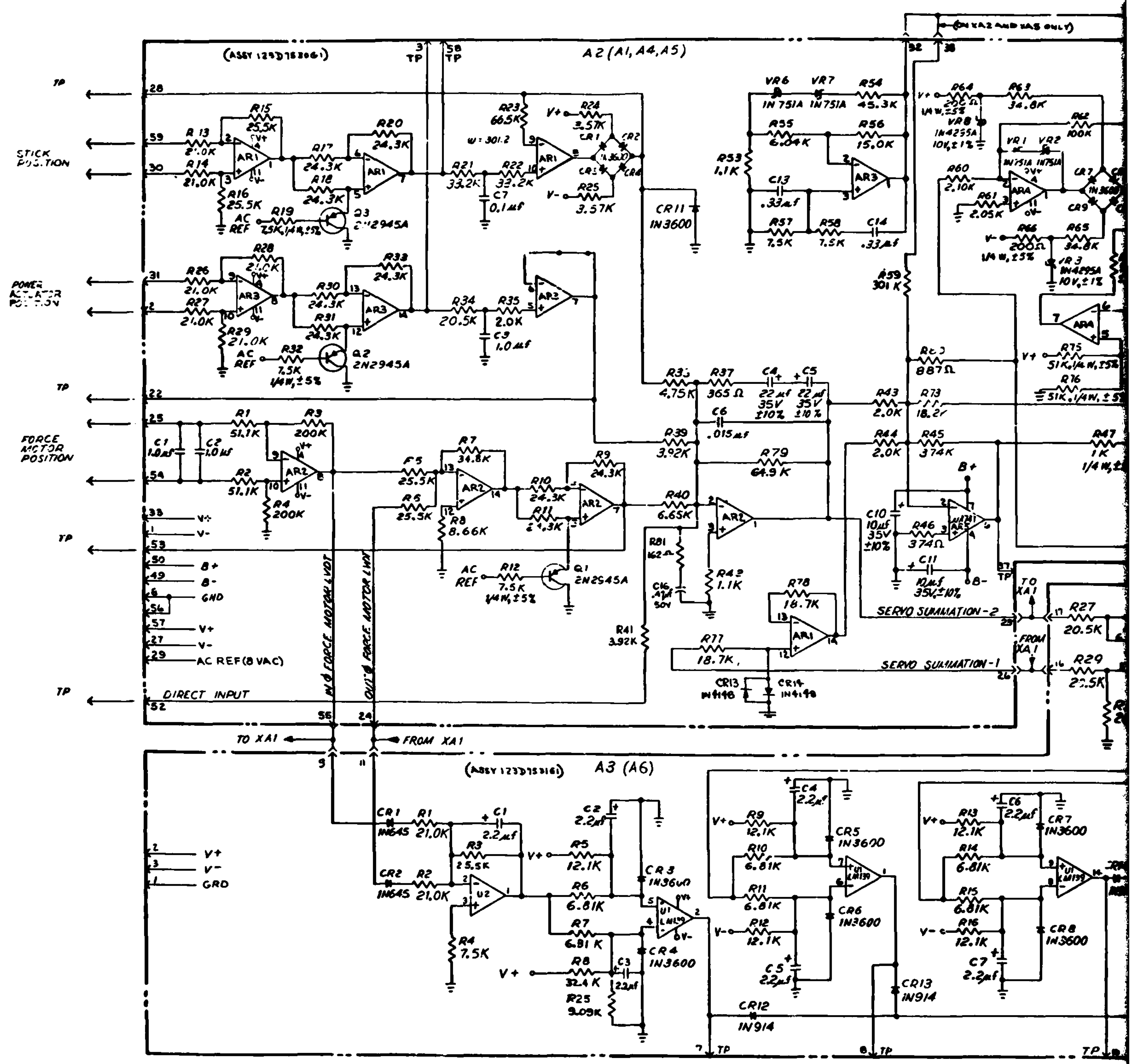


Figure 54. Electrical Schematic, Sheet 1

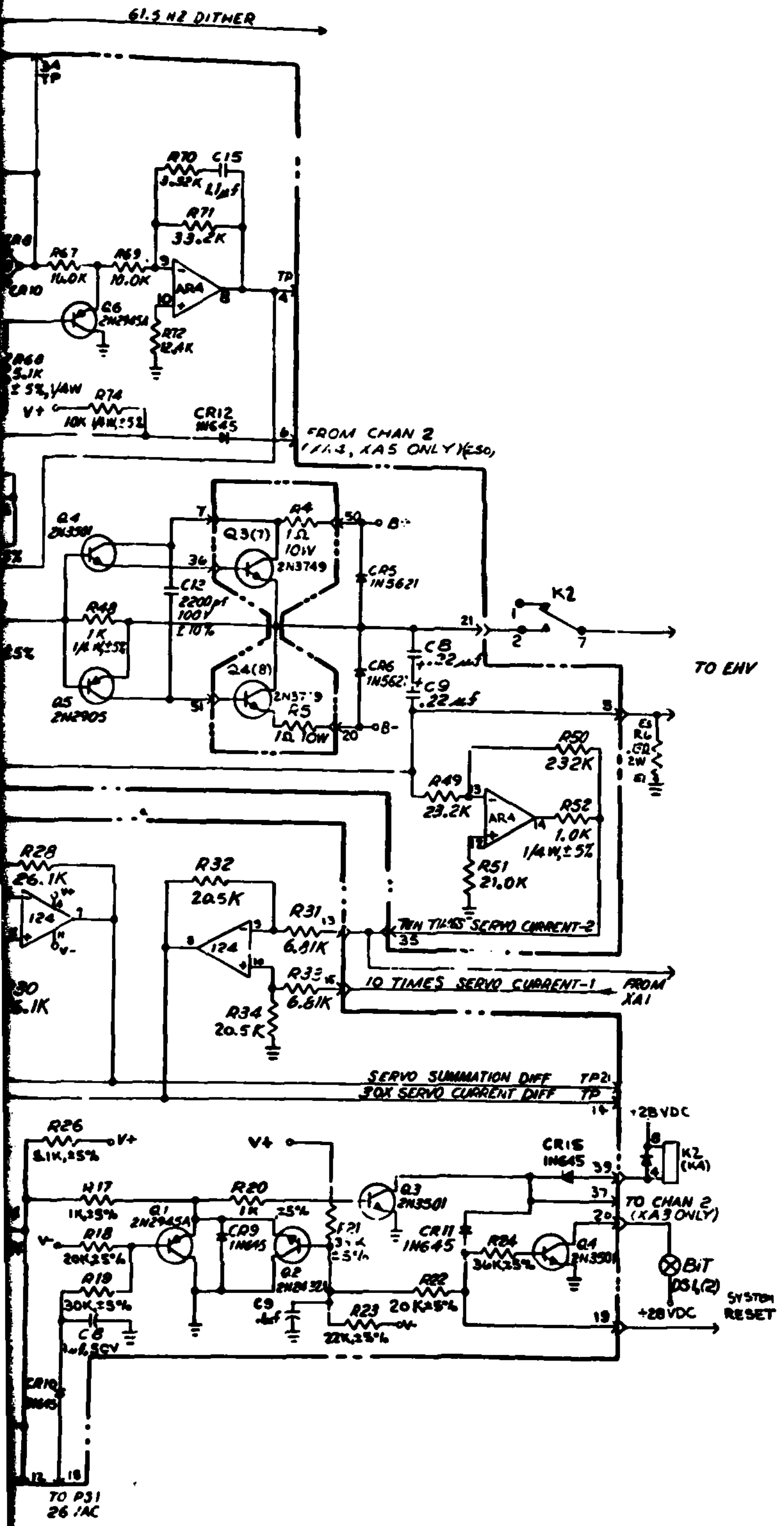
FOR SCHEMATIC OF
XA1,2,3,4,5,& 6
SEE SHEET 2

2



A2 (A1, A4, A5)
(ASSY 123D753061)
A3 (A6)
(ASSY 123D753161)
STICK POSITION
POWER ACTUATOR POSITION
FORCE MOTOR POSITION
TP
AC REF (8 VAC)
DIRECT INPUT
IN Ø FORCE MOTOR LVDT
OUT Ø FORCE MOTOR LVDT
TO XA1
FROM XA1
SERVO SUMMATION-2
SERVO SUMMATION-1
GND
GRD

Figure 55.



Electrical Schematic, Sheet 2

2

The failure detection circuits consist of comparators to measure differences between error voltages or currents in the two signal paths in a channel. If the difference exceeds the failure reference for either polarity, the output amplifier switches from positive to negative saturation. Negative saturation removes the base drive from the transistor which controls the normally energized relay and removes the drive signal to the force motor in the model and command drive circuits. Base drive is also removed by the output of the LVDT self monitor circuit which detects failures in the force motor position feedback LVDT's. The base drive can also be removed by the inverted transistor pair which detects power supply failure, loss of LVDT excitation and B+ and B- individually or collectively. This circuit also functions to provide failure memory. Also if the relay is de-energized, an indicator is illuminated for failure display.

The power supply is a simple full wave supply operating to provide +18 VDC for the B± supply to the servoamplifier output stages. The power supply also provides zener diode regulated ± 12 VDC for the LM 124 operational amplifiers. The nominal input is 110 VAC, 400 Hz and electronic operation is undegraded for input variations of 99.5 to 112.5 VAC.

PACKAGING

The direct drive electronics for the flightworthy system are packaged in a single enclosure containing two channels. The package outline is included as Figure 56. The box volume, less protrusions, is 516 cubic inches and weighs 14.8 pounds. Figure 57 is a view of the front of the unit. Each channel has a test connector, power connector, and a system connector. An indicator lamp displays reset status of each channel. The unit is secured to the airframe by four mounting feet drilled for #10 screws.

Figure 58 is a top view, cover removed, showing the internal arrangement.

The package is symmetrical about the center divider running from front to back. The four circuit boards parallel to the divider each contain a "branch" and are identical. The smaller board at the rear contains failure detection circuits for that channel. Power supplies occupy the center volume in each channel and power dissipating devices are mounted on the rear wall.

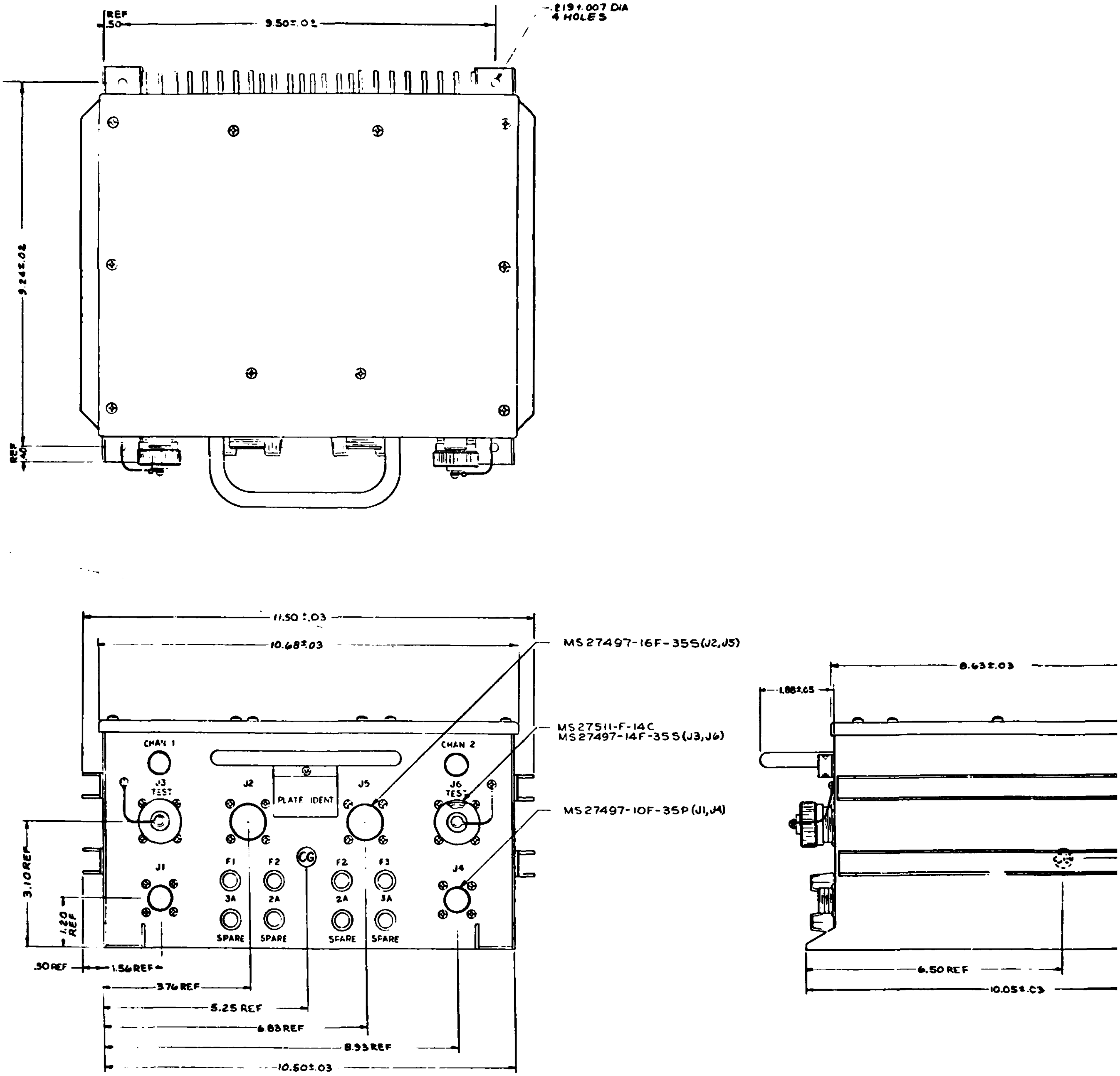
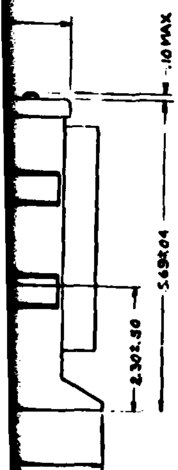


Figure 56. Electronics Outline Drawing



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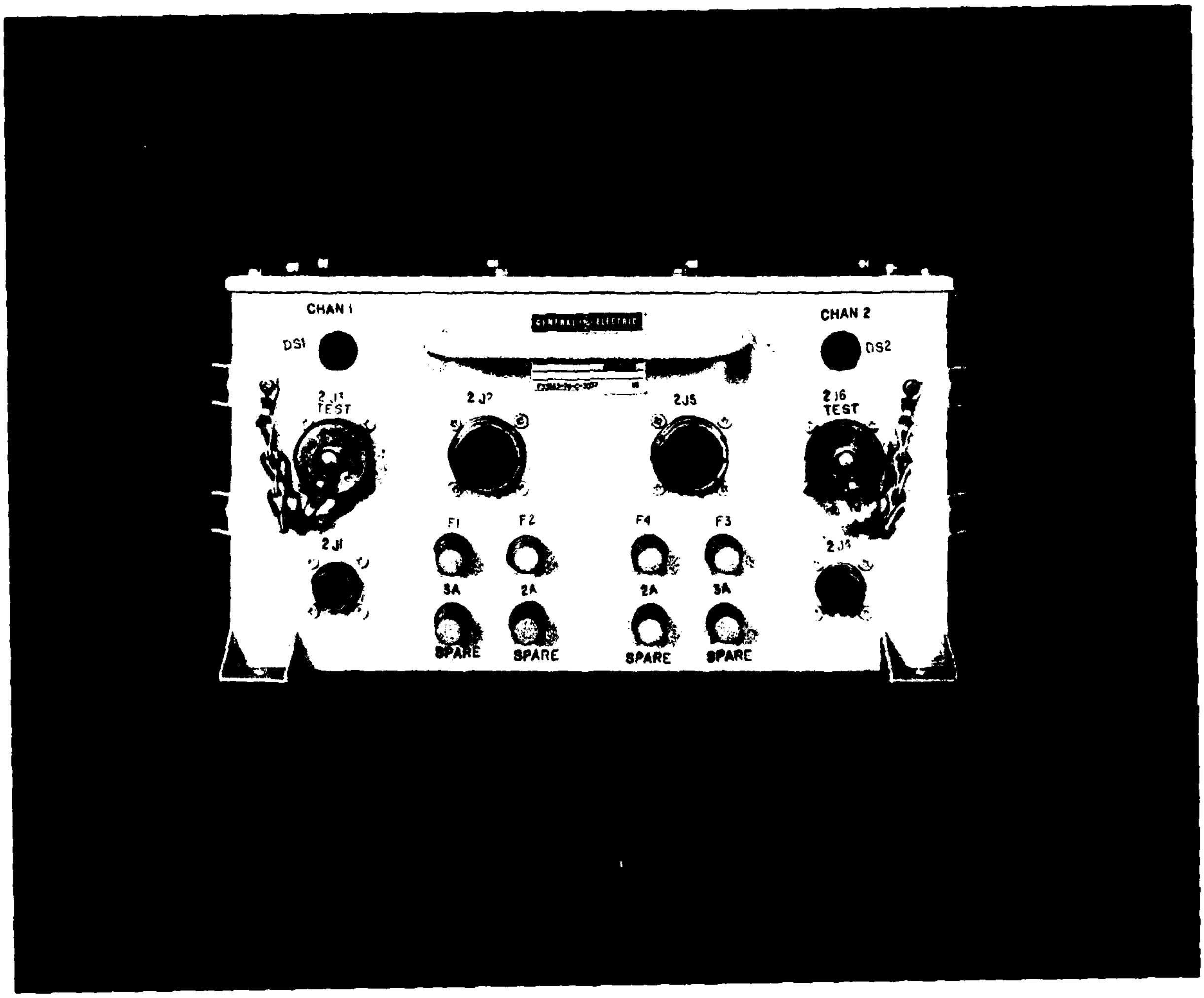

Figure 57. Electronics Unit, Front Panel 26206

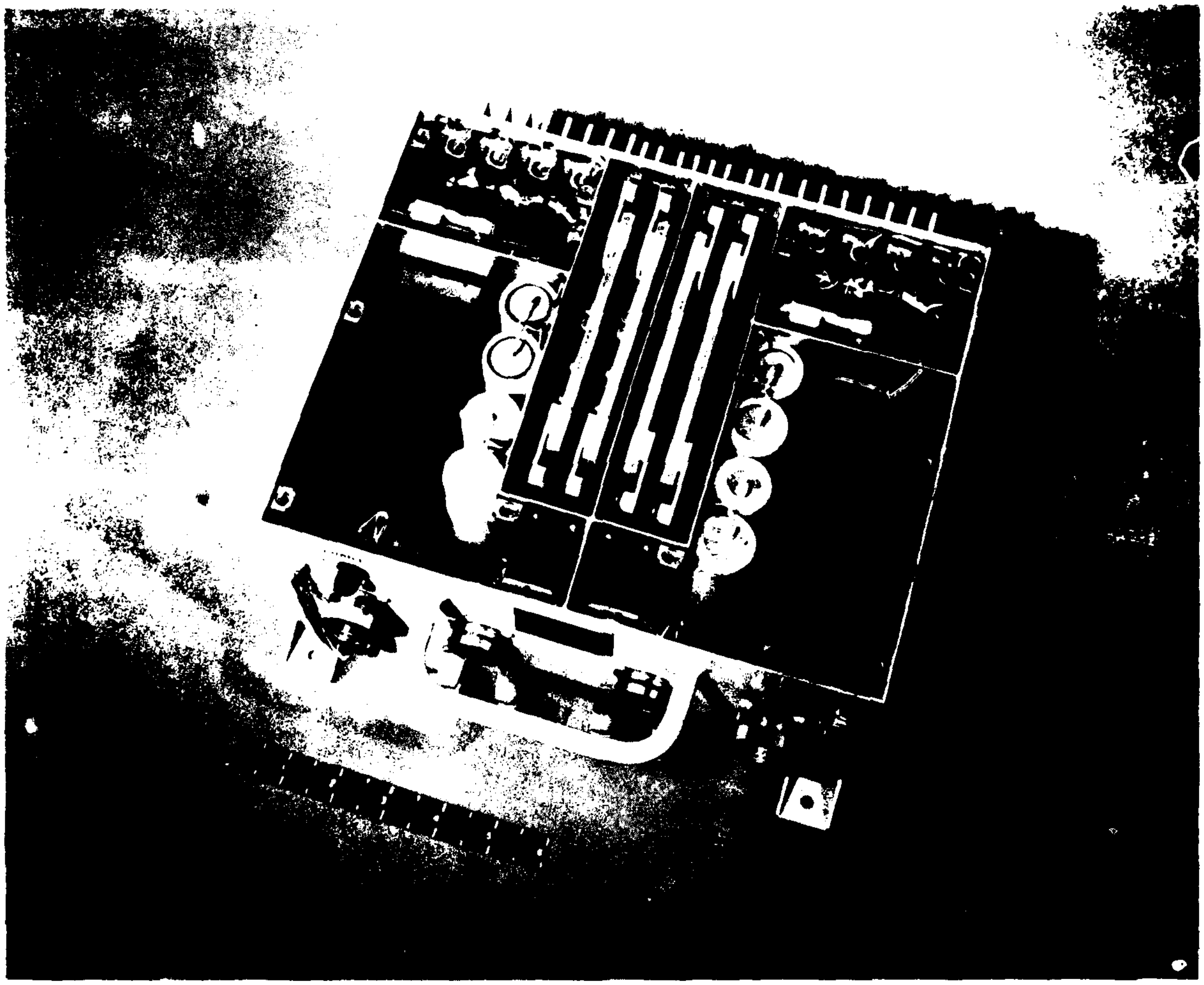

Figure 58. Electronics Unit, Top View 26205

SYSTEM THERMAL CAPACITY

Thermal capacity was measured by commanding saturated current flow into the force motor with both channels on test and recording several temperatures in the electronics and the force motor case temperature. Saturation current with coils at room temperature at 2 amps per coil or 200% of rated output.

Figure 59 is a plot of temperature vs time for the locations noted. The unit is capable of continuous operation at room ambient with saturated output current.

ACTUATOR

DESCRIPTION

The modified actuator is shown complete in Figure 60 and with protective covers removed in Figure 61. The configuration of the flyable actuators is identical to that of the breadboard. The installation drawing of the modified actuator is included as Figure 62. The actuator envelope, as modified, permits installation in either the right or left wing of the F-4 aircraft. Hydraulic connections are unchanged, hence it is only necessary to remove some input control linkage and install as a production actuator. The modified actuator weighs 57.9 pounds.

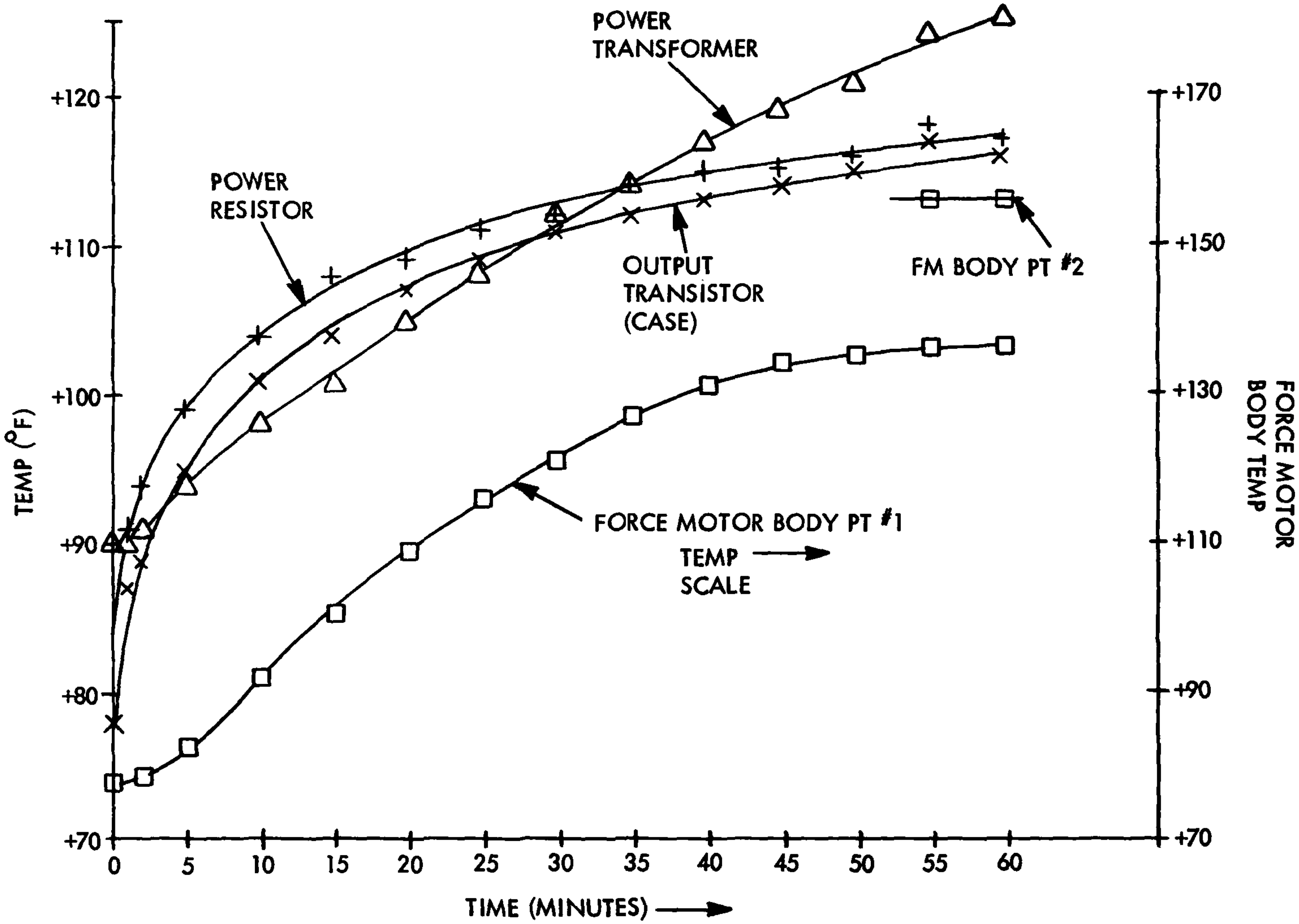

Figure 59. System Temperature Rise at Max. Output

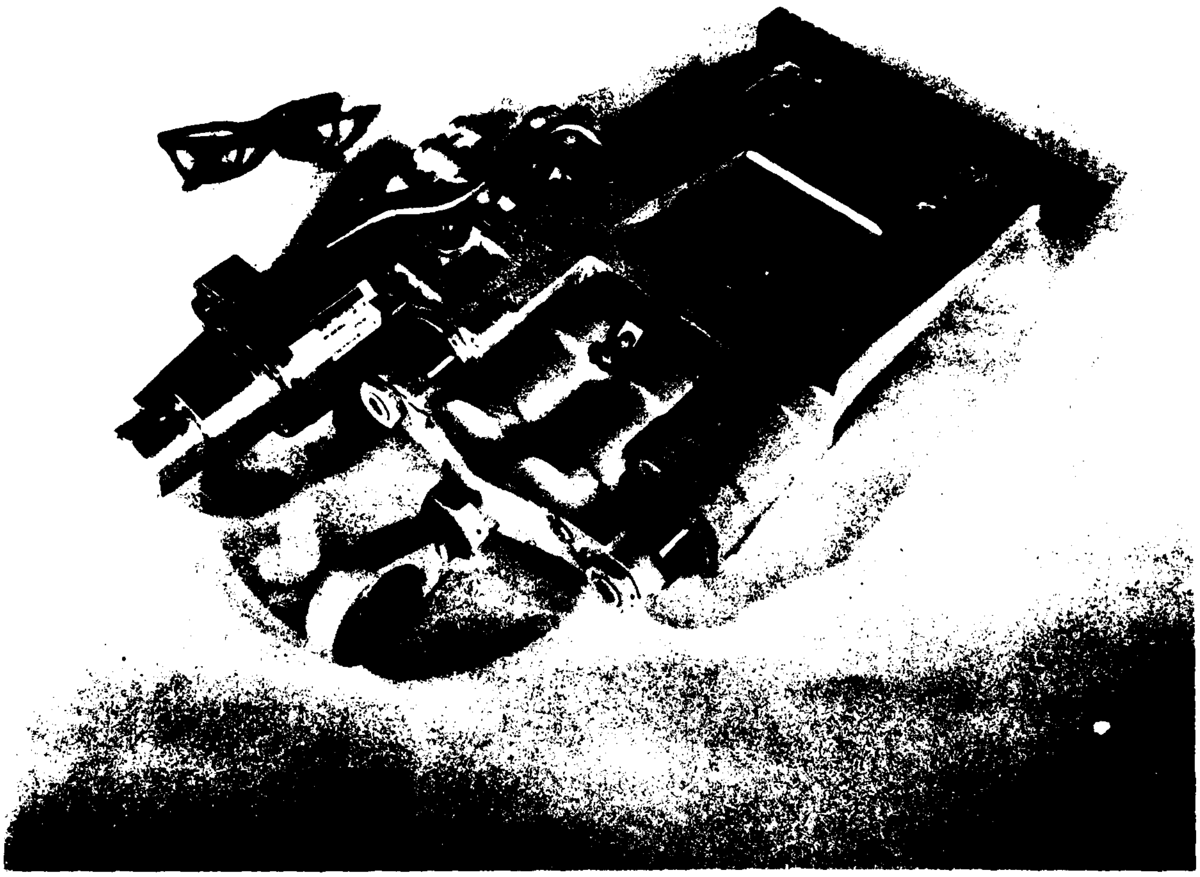

Figure 60. Modified Actuator 26117

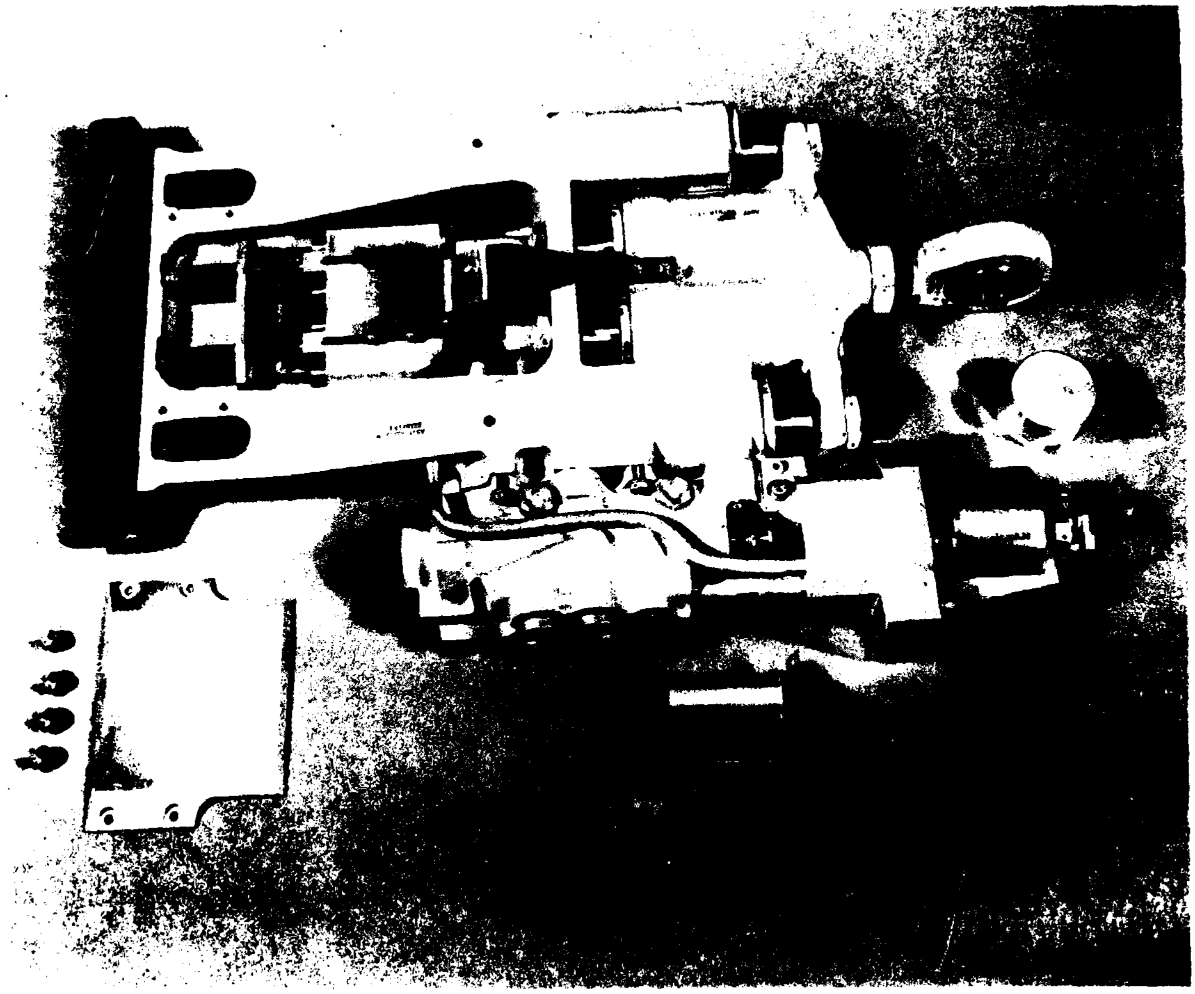

Figure 61. Modified Actuator, Protective Covers Removed 26202

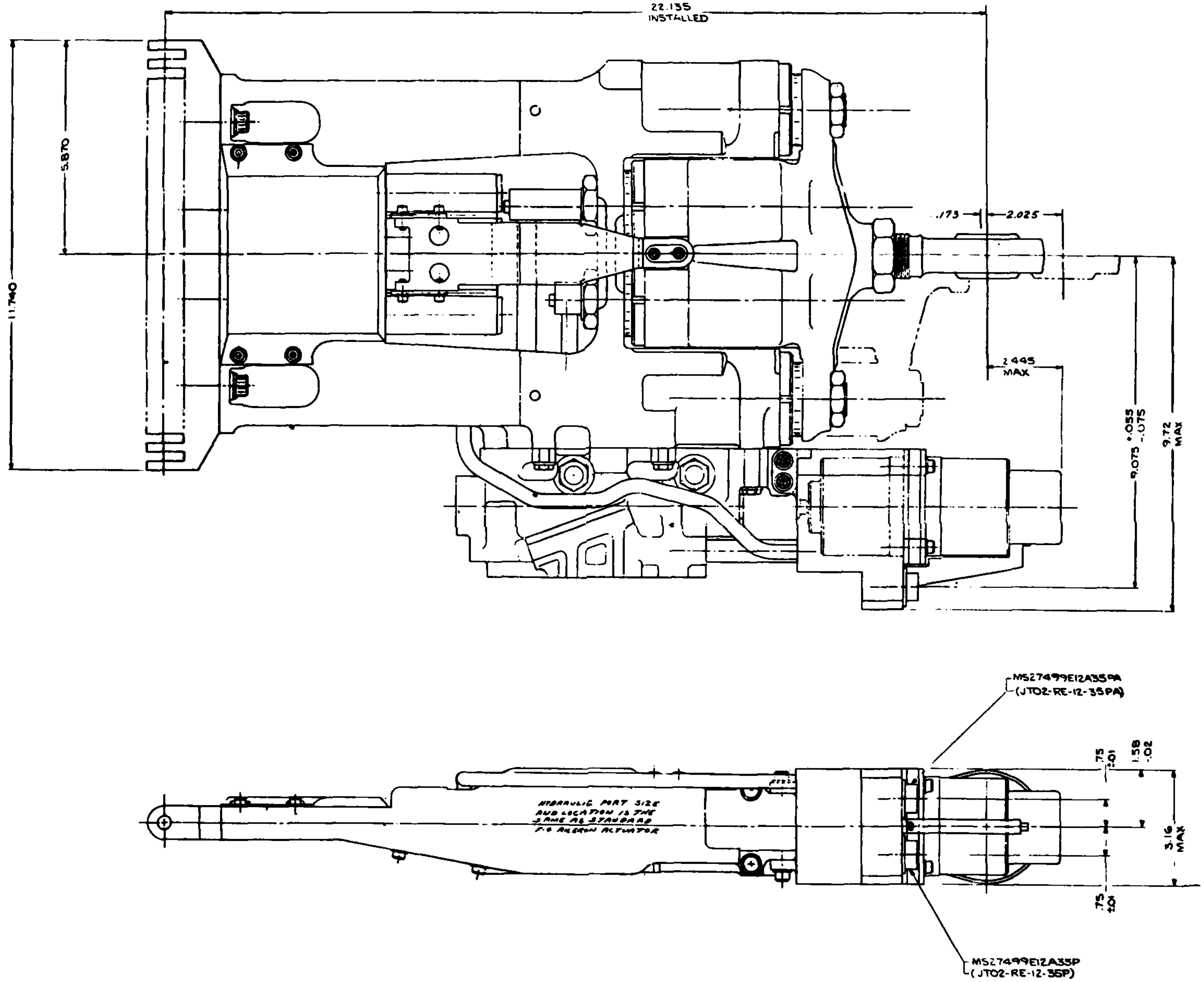

Figure 62. Actuator Installation Drawing

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ACTUATOR AND SYSTEM TESTS

LABORATORY TESTS

The evaluation tests conducted on the flyable system (actuator and electronics) consisted of:

- Frequency Response
- Threshold
- Failure Transients
- Static Stiffness

ACTUATOR FREQUENCY RESPONSE

Figure 63 is an actuator frequency response taken at 10% amplitude to demonstrate compliance with Statement of Work Paragraph 4.3.2 which requires ±3 db at 5 Hz and 10% stroke; phase shift 90 degrees or less at 5 Hz.

THRESHOLD

The actuator threshold was determined by introducing a low frequency sinusoidal signal of slowly increasing amplitude while observing the main ram output on a recorder. The input was noted at the point where the output was clearly following the input signal. Threshold readings were recorded with external tensile loads of zero, 3000, and 6000 pounds. The threshold was unaffected by load and was measured as 2 mv on 6 volts full scale or 0.03%.

FAILURE TRANSIENTS

Figures 64 thru 69 are recorder traces of particular simulated failure situations. Hard failures from null (Figures 64 and 65) produce ram transients equal to 3% of full actuator travel when the failure is introduced in channel 1 which is the controlling channel.

A failure to zero from a trim position, again in channel 1 (Figure 66) results in a transient magnitude of slightly less than 8%.

The effect of any failure in channel 2 is negligible due to the reduced gain in that channel.

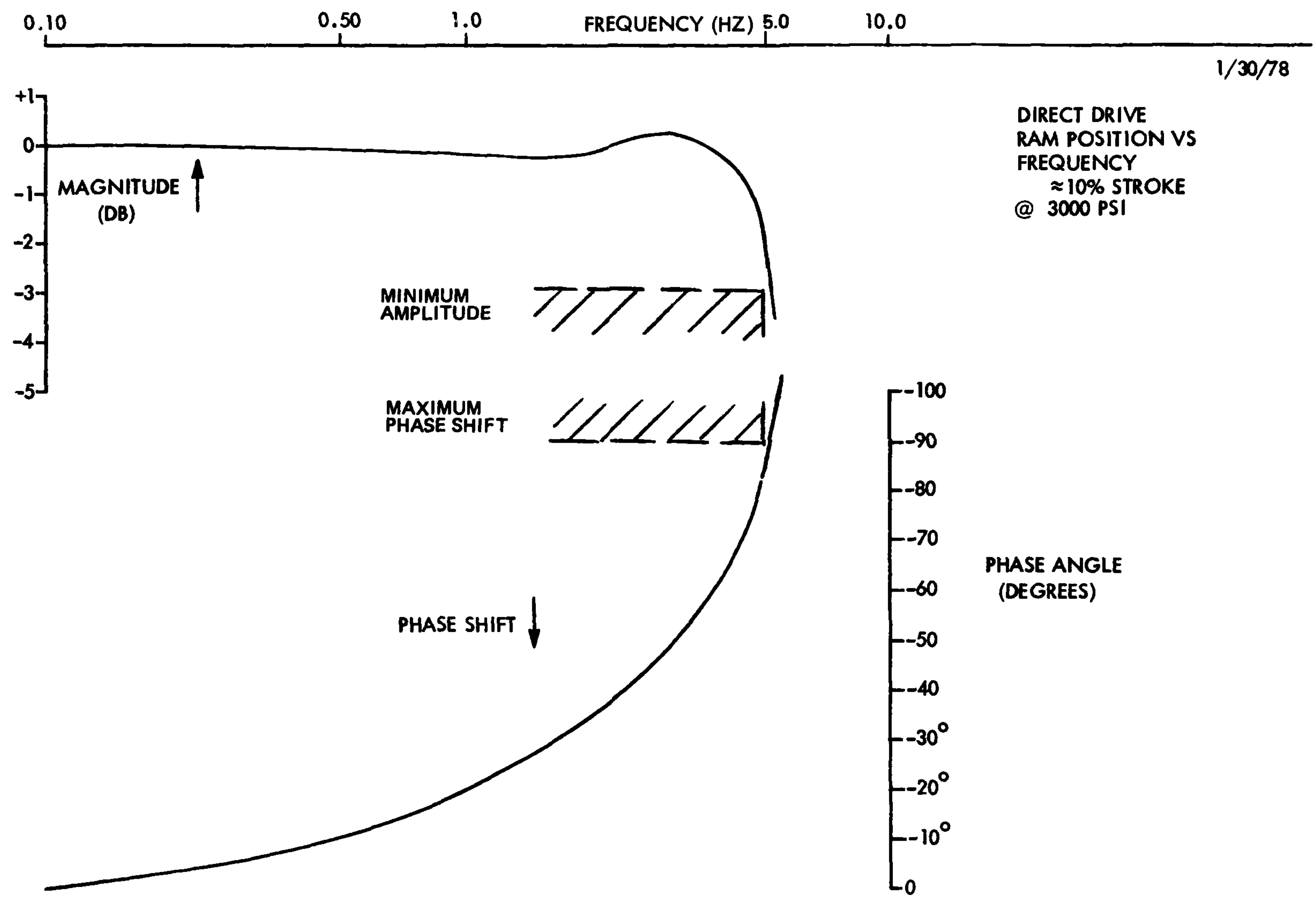

Figure 63. Actuator Frequency Response

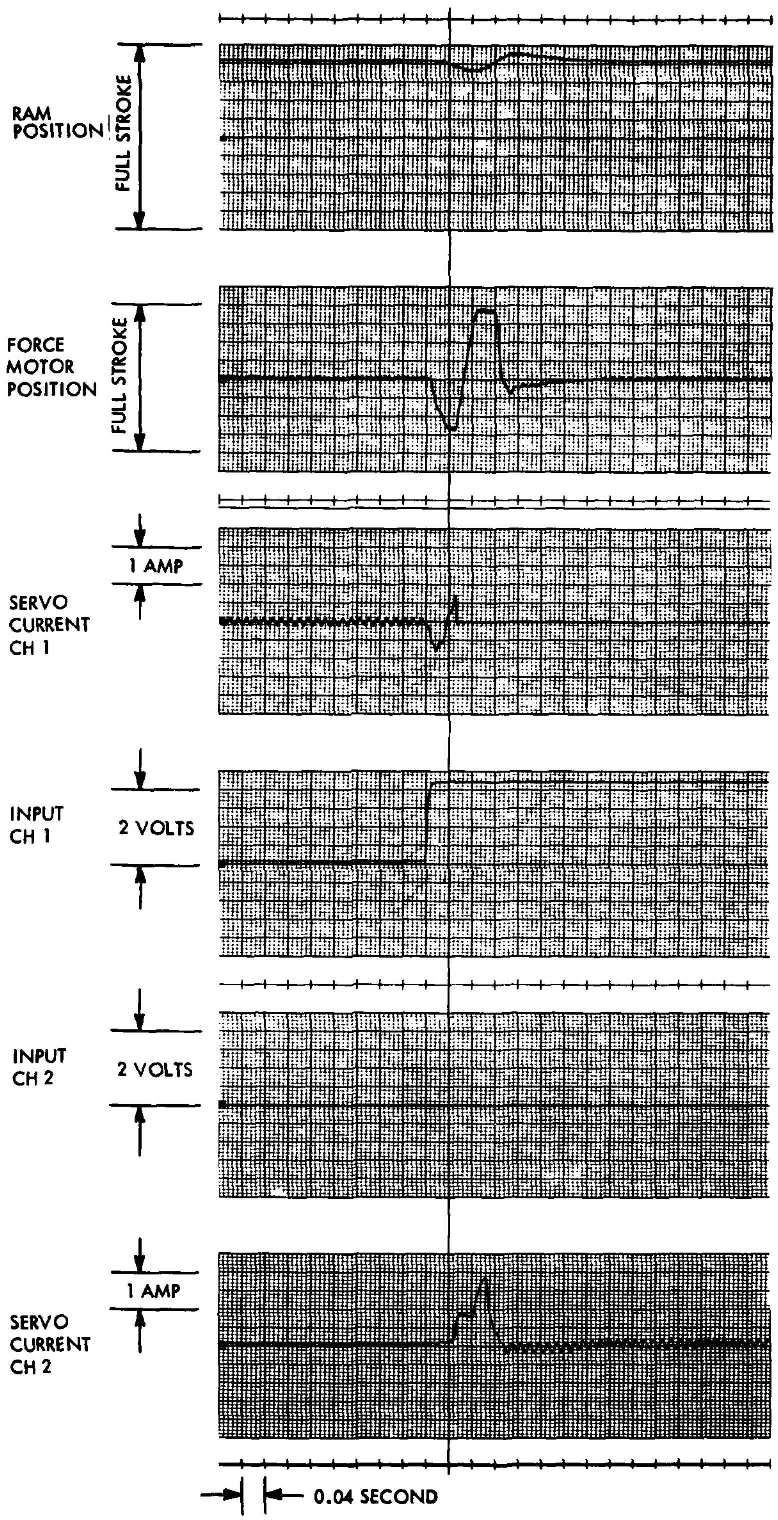

Figure 64. Failure Transients, Channel 1 Extend Failure

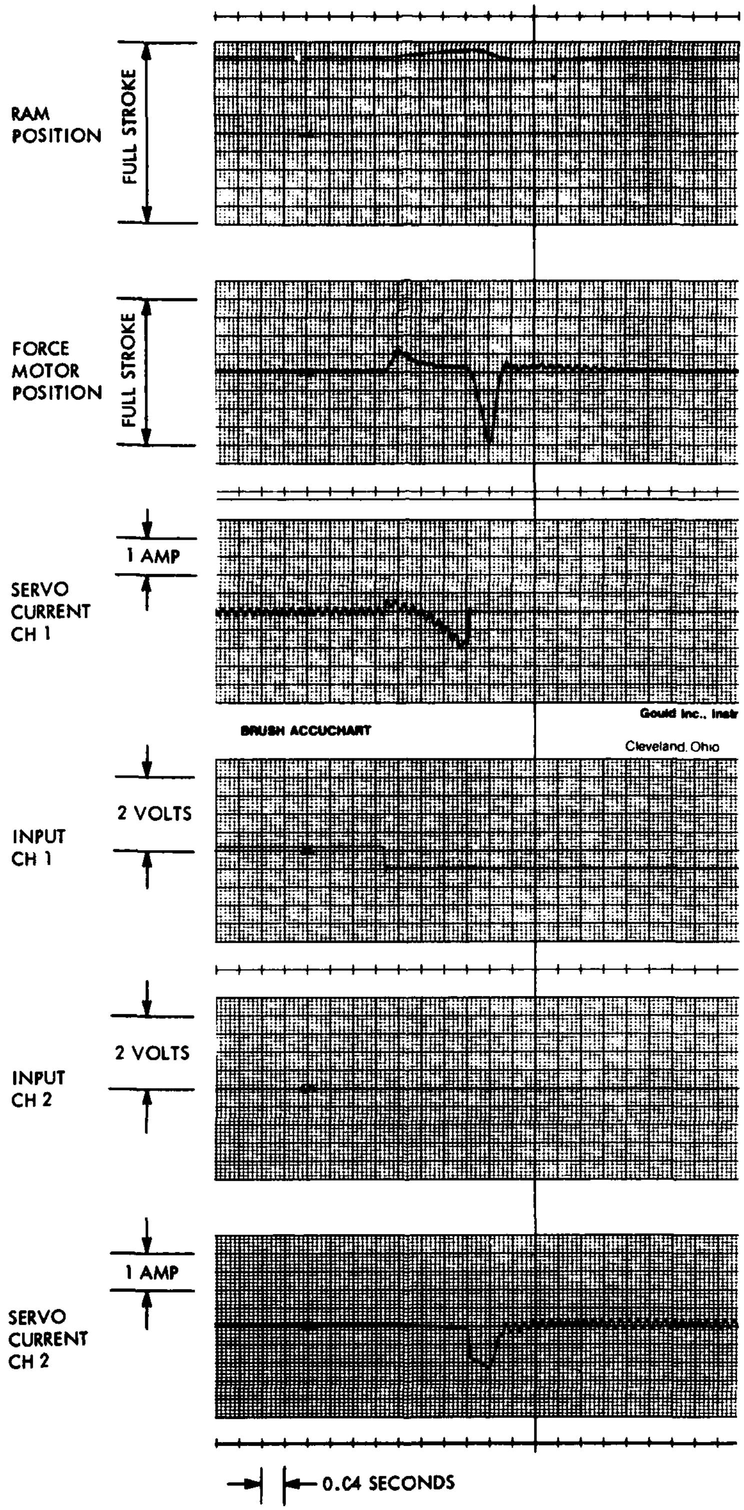

Figure 65. Failure Transients, Channel 1 Retract Failure

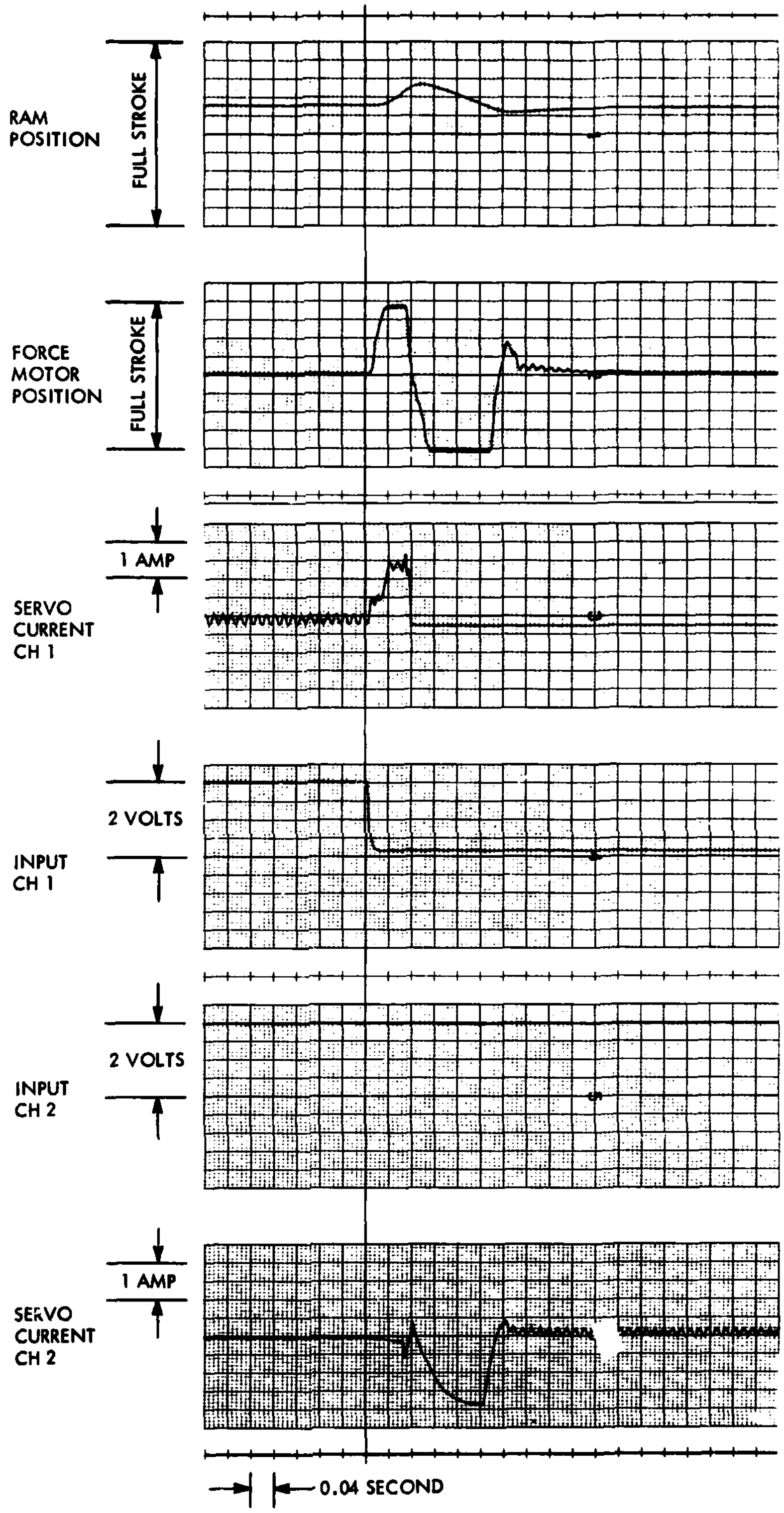

Figure 66. Failure Transients, Channel 1 Failure to Zero

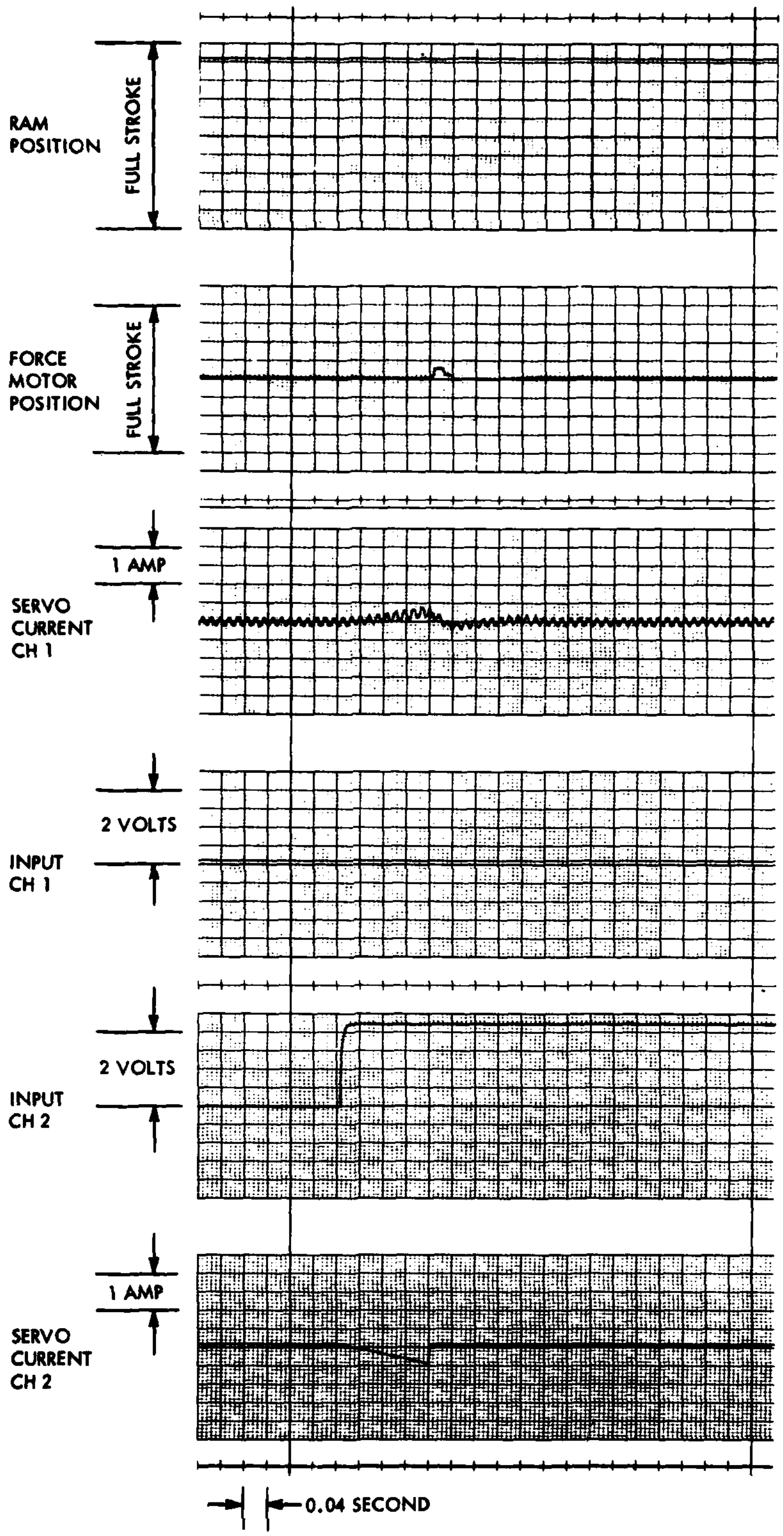

Figure 67. Failure Transients, Channel 2, Extend Failure

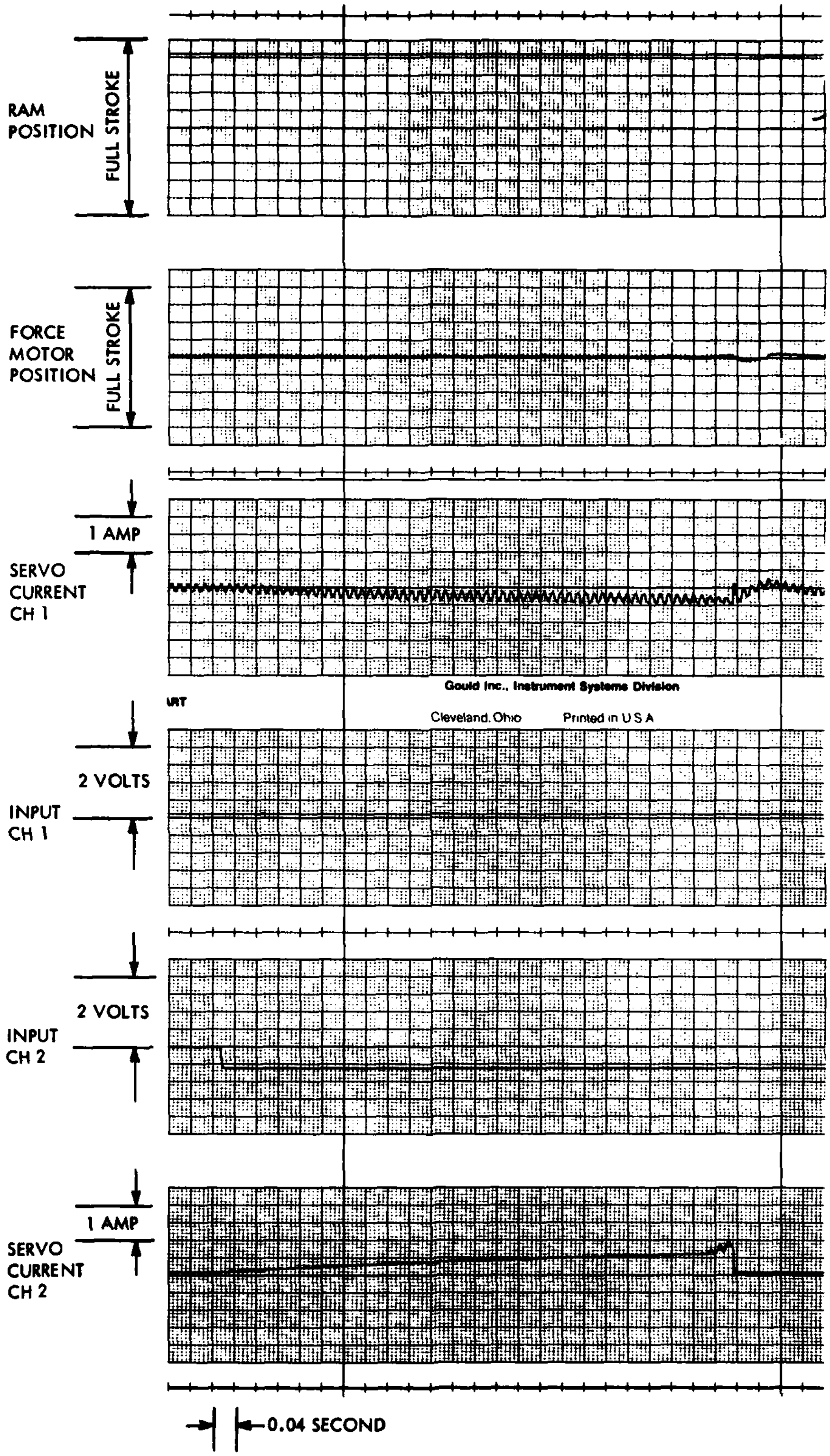

Figure 68. Failure Transients, Channel 2 Retract Failure

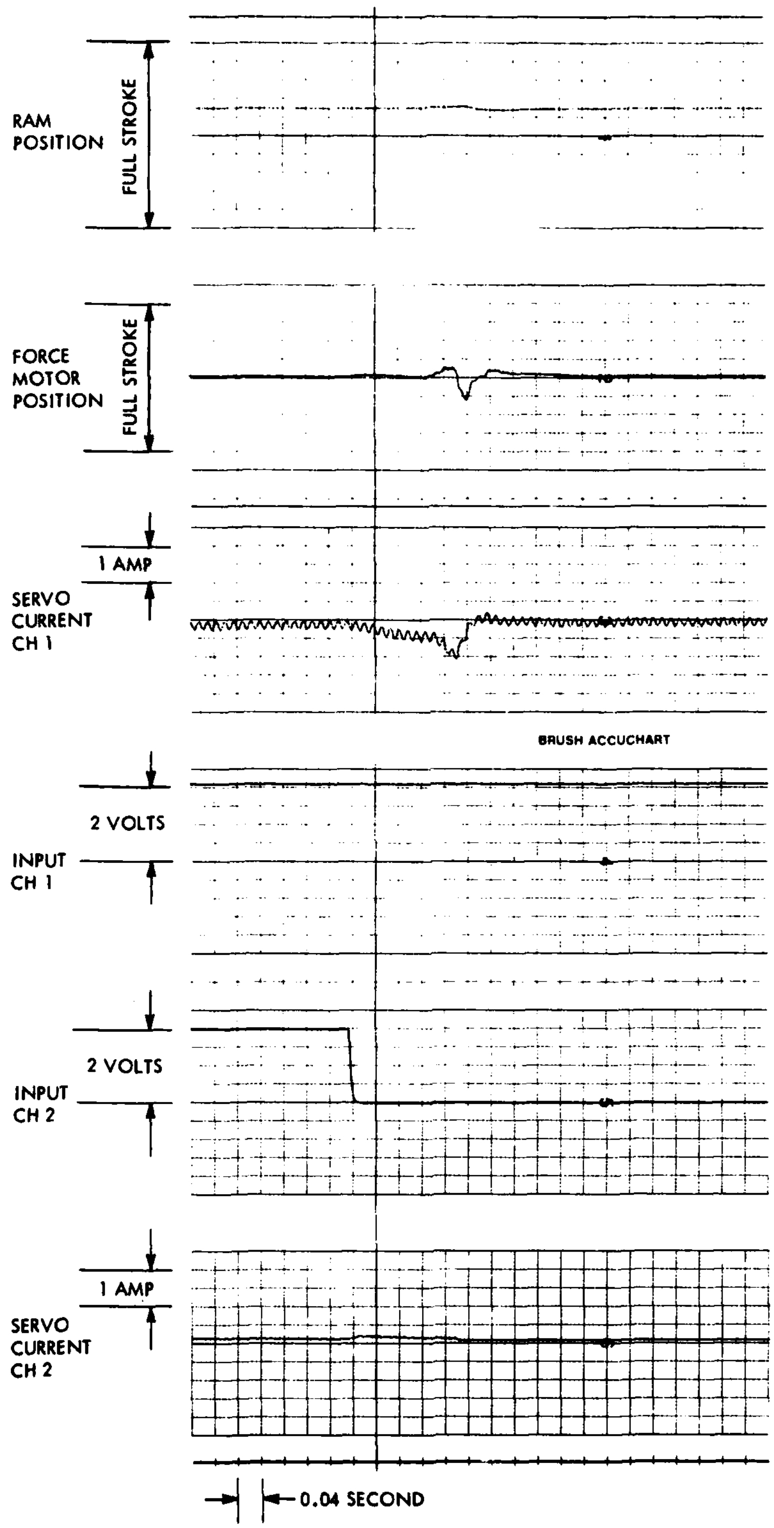

Figure 69. Failure Transients, Channel 2 Failure to Zero

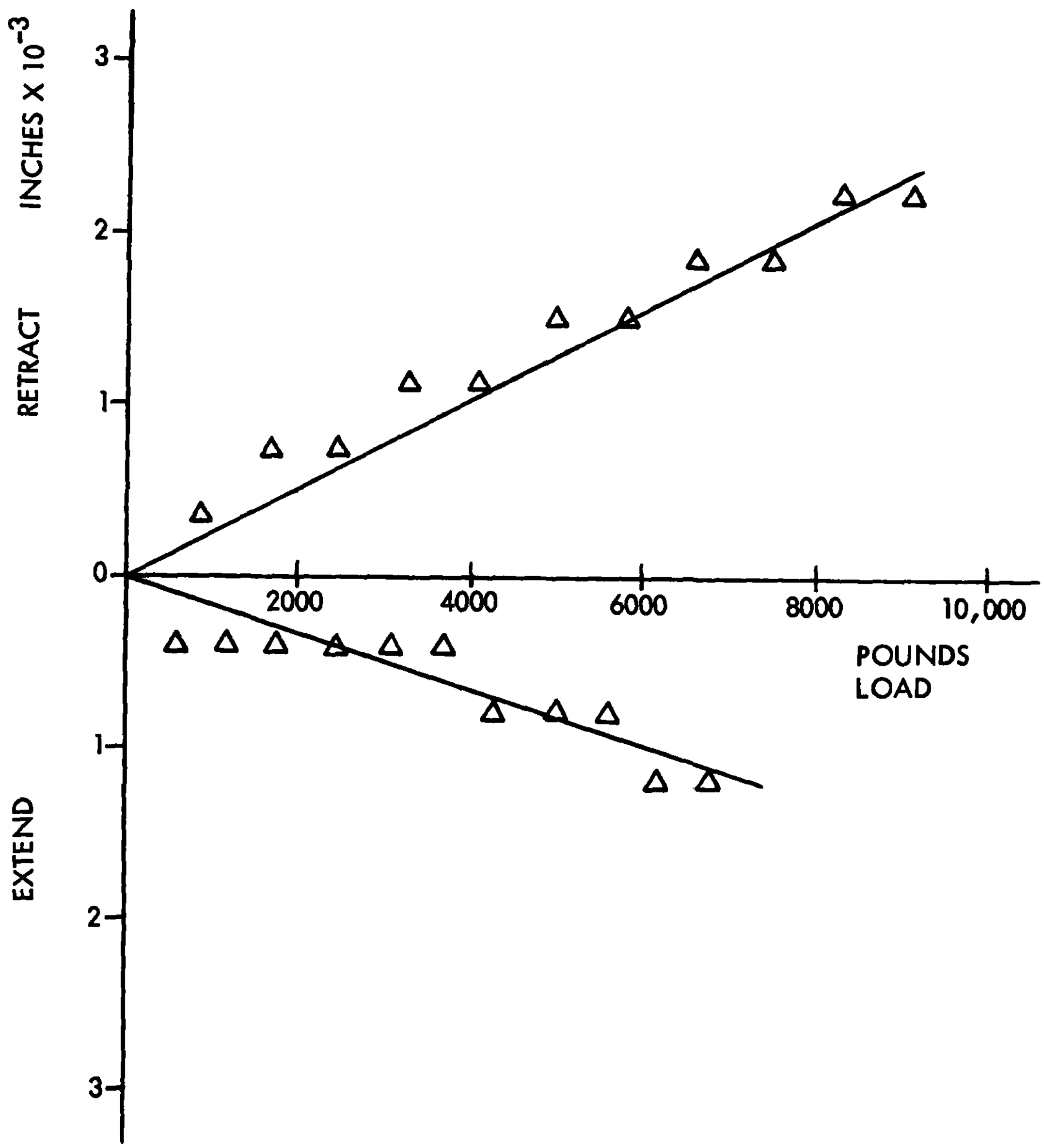

Figure 70. Static Stiffness

STATIC STIFFNESS

The closed loop stiffness of the actuator was measured by loading the actuator by means of an external cylinder connected to a variable pressure source. The main ram LVDT's provided a means of measuring actuator displacement. Figure 70 is a plot of displacement vs load for retract and extend force application. The stiffness in the retract direction is 2.6×10^{-7} inches/pound and is 1.6×10^{-7} inches/pound in the extend direction.

SYSTEM TEST SUMMARY

The laboratory evaluation of the flyable system corresponded closely with the breadboard test results. The new actuator valve friction was substantially lower than the friction measured on the old actuator used for the breadboard. The dither signal could have been reduced or eliminated but without knowledge of the end-of-life friction, the dither signal level was not changed.

ENVIRONMENTAL TESTS

To establish the flight worthiness of the system, the tests identified in Table 3 were conducted. The test environments specified by MIL-STD-810B include:

Vibration	Method 514.1, Figure 514.1-1 Curve M
Temperature Altitude	Method 504, Procedure 1, Class 1, Steps 2, 6 and 11
Humidity	Method 507, Procedure 1, One 24 Hour Cycle
Shock	Method 516, Procedures I and III

The extreme temperature and endurance cycling tests on the actuator were conducted in accordance with MIL-C-5503C:

Extreme Temperature	Paragraph 4.7.7.1 and 4.7.7.3
Endurance Cycling	Paragraph 4.7.8, 10^6 cycles

All environmental tests were completed satisfactorily. The equipment is suitable for flight test in an F-4 aileron channel.

EMI on the system was conducted in accordance with MIL-STD-461:

Radiated Electric Field RS03

10.0 KHz - 1.99 MHz, 3 volts/meter
2.0 MHz - 29.99 MHz, 5 volts/meter
30.0 MHz - 180.0 MHz, 10 volts/meter

TABLE 3

ENVIRONMENTAL TESTS

Test	Electronics	Actuator	System
Vibration	●	●	
Temp-Altitude	●		
Operating Shock	●		
Crash Safety Shock	●		
Humidity	●		
Extreme Temperature		●	
Endurance		●	
EMI			●

SECTION IV

CONCLUSIONS

The Bi-Directional Force Motor design described herein met the requirements of the specification for force output and bandwidth. The device is simple and rugged mechanically and with a minimum of moving parts not subject to jamming failure modes.

The same features result in an easily produced and economical component.

The capacity for redundant input coils makes the unit amenable to various redundancy management approaches.

The specification of the force motor is summarized below:

Stroke	±0.065 inches
Force at Center Stroke	80 pounds
Number of Coils	4
Coil Resistance	5.2 ohms
Force Gradient	20 pounds/amp
Power @80 lbs	20 watts (4 coils)
Weight	7.2 pounds

Significant improvement in future high reliability flight and engine controls can be achieved by using high force level motors in lieu of redundant hydraulic driver actuators.

The modified F-4 aileron actuator incorporation the direct drive control valve and attendant electronic drive assembly package developed and tested during this program are considered flightworthy and ready for flight testing in an F-4 aircraft to fully demonstrate the feasibility of the direct drive technique for use in fly-by-wire flight control systems.

APPENDIX

TEST PLAN FOR TESTING BREADBOARD DIRECT DRIVE ACTUATOR

REVISIONS

LETTER	PAGE NO.	DESCRIPTION	DATE	APPROVED
A	6	Section 5.1.2 Second paragraph; Figure 1 reference corrected to Figure 2	8/4/76	JCR 8/5/76
A	6	Section 5.1.2 Third paragraph; Deleted V5	8/4/76	JCR 8/5/76
A	6	Section 5.1.3 Second paragraph; corrected servoamplifiers to servoamplifier	8/4/76	JCR 8/5/76
A	7	Section 5.1.3 Step 1; Figure 2 reference corrected to Figure 1	8/4/76	JCR 8/5/76
A	26	Figure 6 revised based on Data from National Water Lift Co.	8/4/76	JCR 8/5/76
A	27	Figure 8 revised so that large area of Load cylinder applies force to large area of Aileron actuator	8/4/76	JCR 8/5/76

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LIST OF FIGURES

1.0 SCOPE

1.1 GENERAL

This test plan establishes the individual test procedures for tests to be conducted on the Breadboard Direct Drive Actuation System components, subassemblies and system.

2.0 APPLICABLE DOCUMENTS

2.1 SPECIFICATIONS

USAF Contract F33615-76-C-3037, Section F-Description/Specifications, Statement of work for development of Direct Drive Control, Valve for Fly-By-Wire Flight Control Actuators

3.0 GENERAL REQUIREMENTS

This procedure covers the tests to be performed on the Breadboard Direct Drive Actuation System.

3.1 ENVIRONMENTS

All tests shall be performed under normal room temperature and atmospheric conditions.

3.2 ELECTRICAL REQUIREMENTS

115 VAC, 400 Hz
28 VDC

3.3 HYDRAULIC REQUIREMENTS

0-3000 PSI, 0-34 GPM

3.4 DATA RECORDING

Test data will be recorded on test data sheets and specific data recording equipment as required by the individual test procedures.

4.0 TEST EQUIPMENT

Dial Indicator: Model E-18-U, .001" inch or equivalent
Manufacturer - Federal

Calibrated Weights: .5, 1, 2, 2.5, 4, 5, 10, 20 pound weights

Vacuum Tube Voltmeter: Model 5640 or equivalent,
Manufacturer - Dava

Ammeter: Model 370 or equivalent
Manufacturer - Weston

Frequency Response Analyzer: EMR Model 1410 or equivalent
Manufacturer - Weston

Strip Chart Recorder: Model 320 or equivalent
Manufacturer - Sansborn

Force Scale: Model 1-10-M or equivalent
Manufacturer - Hunter

Pressure Gages: Models H26561, H15004, H14160 or equivalent
Manufacturer - Heise

Flow Meters: Model B7-17-600/70
Manufacturer - F. & P. Co.

Hydraulic Test Stands: G E. Facility No. 14478
Capacity - 34 GPM at 3000 psi
Greer Hyd. Inc. Model Z652R
Capacity - 10 GPM at 5000 psi

Actuator No Load Test Fixture: GE P/N 223E937 Modified with
Adaptors to Hold Aileron Actuator

X-Y Recorder: Model 1100 or equivalent
Manufacturer - EAI

Actuator Vibration, Stiffness, Endurance Test. Fixture: GE P/N T.B.A.

5.0 TEST PROCEDURES

5.1 FORCE MOTOR

The following tests will be performed to measure the performance of the bi-directional, Linear Motion Force Motor.

5.1.1 FORCE MOTOR CENTERING SPRING FORCE VS POSITION

Using the test set up shown in Figure 1, calibrated weights are added in increments and the deflection measured by a dial indicator with 0.001 inch graduations. The Force motor, will first be positioned so that calibrated weight (Force) is in the extend direction. The Force motor position will then be reversed to measure the retract centering spring force vs position.

5.1.2 FORCE MOTOR POSITION VS CURRENT (POSITION GAIN) AND HYSTERESIS, NO EXTERNAL LOAD, OPEN LOOP

The force motor will be positioned as shown in the test set up shown in Figure 1.

Each coil and series resistor, for individual coil current measurement, will be connected in parallel to a single current feedback servoamplifier as shown in Figure 2.

The Voltage signal to the servoamplifier, V_i, will be increased to cause full force motor extend position from center, decreased to a negative value causing full retract position and then increased to zero where the force motor is back to center position. As the voltage, V_i, is changed in discrete steps, the voltages V_0, V_1, V_2, V_3, V_4, and the output position will be recorded to obtain data for plotting force motor gain and hysteresis curves.

The previous test procedure will be repeated twice with only coils 1, 2, and 3 connected and then with only coils 1 and 2 connected to determine force motor gain with 3 or 2 coils operating.

5.1.3 FORCE MOTOR OUTPUT CAPABILITY OVER STROKE, OPEN LOOP

The force motor will initially be positioned as shown in the test set up presented in Figure 1.

The four coils of the force motor will be connected to the servoamplifier as shown in Figure 2.

5.1.3 Cont.

STEP 1

The voltage V_i will be increased to a value to position the force motor armature at full retract, and the current required to hold this position will be recorded. A calibrated weight will be attached to the armature output shaft causing a force and deflection in the extend direction as shown in Figure 1. The voltage V_i will be increased to a value such that full retract position is again achieved and the current value recorded. Voltage V_i will be decreased in discrete increments and the armature position and current recorded at each increment until full extend position is achieved.

STEP 2

The voltage V_i will be increased to return the armature back to full retract position. Another weight will be added and the procedure of Step 1 repeated. If full retract, position cannot be achieved due to increased weight and force motor saturation, the maximum position and current required will be recorded.

STEP 3

Steps 1 and 2 will be repeated for additional weight additions up to a maximum weight that is equal to or greater than 80.0 pounds.

STEP 4

The weights will be removed and the force motor position reversed from that shown in Figure 2. The voltage V_i will be increased to a value which positions the armature at full extend position. Weights will be added to cause retract deflections, and the procedures of 1, 2 and 3 will be repeated.

The data obtained from steps 1, 2, 3 and 4 above will be used to plot a family of curves of position vs current at different loads which will represent the open loop force capability of the bi-directional Force Motor.

STEP 5

The previous steps 1, 2, 3 and 4 will be repeated with only coils 1 and 2 of the force motor connected and a maximum weight equal to or greater than 40.0 pounds.

5.1.4 CLOSED LOOP FORCE MOTOR POSITION GAIN

The force motor (F.M.) will be positioned as shown in Figure 1.

The force motor coils will be connected to the breadboard servoamplifiers and the F.M. position LVDT's will be connected to the position feedback electronics as shown in Figure 3. The F.M. position LVDT's will be nulled at the centered position of the F.M.

STEP 1

The common input command to the dual servoelectronics will be varied from zero to full extend position command, then to full retract command and back to zero in discrete steps with the output position, F.M. current and common input command recorded.

STEP 2

Step 1 will be repeated with only coils 1 and 2 of the Force Motor connected.

5.1.5 CLOSED LOOP FORCE MOTOR STIFFNESS

The force motor (F.M.) will initially be positioned as shown in the test set up of Figure 1.

The force motor coils will be connected to the breadboard servoamplifiers and the F.M. position LVDT's will be connected to the position feedback electronics as shown in Figure 3. The F.M. position LVDT's will be nulled at the centered position of the F.M.

STEP 1

With the common input command to the dual servoelectronics set at zero corresponding to centered F.M. position, calibrated weights will be added causing the F.M. position to extend. For each increment in added weight up to a maximum of 80.0 pounds the corresponding position and current will be recorded.

STEP 2

Increase the common input to a value ($\pm$ V) which causes 50% of Full F.M. extend position. Repeat Step 1.

5.1.5 Cont.

STEP 3

Repeat Step 1 with common input command set at 90% of Full F.M. extend position.

STEP 4

Repeat Step 1 with common input command set at 50% of Full retract position.

STEP 5

Repeat Step 1 with common input command set at 90% of Full retract position.

STEP 6

Reverse the position of the Force motor from that shown in Figure 1 and repeat Steps 1, 2, 3, 4 and 5.

STEP 7

The previous steps 1, 2, 3, 4, 5 and 6 will be repeated with only coils 1 and 2 of the force motor connected and a maximum weight equal to or greater than 40.0 lbs.

5.1.6 CLOSED LOOP FORCE MOTOR FREQUENCY RESPONSE AND THRESHOLD TEST

The force motor will be positioned as shown in Figure 1 and connected to the breadboard servoelectronics as shown in Figure 3. The output of the EMR Frequency Analyzer will be connected to the common command input of the servoelectronics and the channel 1 F.M. position feedback signal will be connected to the input of the frequency analyzer.

STEP 1

The initial frequency will be to set at 0.1 Hz and the amplitude adjusted to achieve $\pm$ 10% of full F.M. position. The freqeuncy will be changed in discrete steps from 0.1 Hz to 30 Hz or that frequency which results in 180° phase shift. The F.M. output position amplitude and phase shift will be recorded. Input command, position feedback voltages, and coil voltages proportional to current will be recorded on a multi channel strip chart recorder.

STEP 2

Repeat Step 1 with amplitude set at $\pm$ 50% of Full F.M. Position.

STEP 3 THRESHOLD TEST

Set the frequency analyzer amplitude at a value that will cause $\pm$ 100% of full force motor position at a frequency of 0.159 Hz (1.0 rad./sec.). Record this value of

5.1.6 Cont.

imput amplitude. With the input amplitude and F.M. output position LVDT feedback voltage being recorded on the strip chart recorder, slowly decrease the input amplitude until no output motion from the F.M. is detected. Record the input amplitude value where output motion stops.

STEP 4

Repeat Steps 1, 2 and 3 with only coils 1 and 2 of the Force Motor connected.

5.2 F-4 AILERON ACTUATOR CONTROL VALVE TESTS

The following tests will be conducted on the F-4 aileron actuator control valve to determine frictional force, flow force and flow output of the control valve as a function of spool position.

5.2.1 VALVE FRICTION FORCE VS SPOOL POSITION

Connect the F-4 Aileron Actuator to the Hydraulic Test Stand as shown in Figure 4A. The schematic of the Hydraulic Test Stand is shown in Figure 5. Connect R_1, P_1, and R_2 of the actuator to return port 1 of the Test Stand. Attach the Adjusting Screw/Force Scale Fixture to the adaptor frame on the control valve housing and the dial indicator to the valve housing to measure spool position.

Before starting any tests open or close the following valves:

1. Open shut off valves (SOV) A, B and return port SOV 3
2. Close SOV C to the 20 GPM flowmeter on Test Stand
3. Close return port SOV 2
4. Open return port SOV 1
5. Open SOV S1 and R1 to supply & return test gages
6. Close pressure port SOV's 1, 2 and 3 on the Test Stand

With reference to Figure 5, open the SOV's to the system pressure gage, pump system pressure gage and the return system pressure gage. Open the bypass valve and turn down the system pressure regulator.

Turn on the test stand pump and open pressure port SOV 2 to the actuator. Check for leakage at all connections. Slowly close bypass valve and adjust pressure regulator to maintain less than 50 psi at supply pressure gage until bypass valve is completely closed.

If the spool valve is extended into housing from neutral some flow should be observed on the O-5 GPM flowmeter and the actuator cylinders should drift to full extend position. If the supply pressure is 50 psi and the cylinders are retracted turn the adjusting screw to cause the valve to extend until the cylinders start to drift to extend position and flow is observed through the flowmeter.

Slowly increase the supply pressure by turning up the system pressure regulator. At the same time, turn the adjusting screw to position the valve spool to maintain less than 1.0 GPM flow through the 5 GPM flowmeter. Check for leakage at all connections as pressure is increased. Turn the system pressure regulator to obtain a supply pressure of 1000 psi above return pressure and adjust the spool valve to obtain minimum (zero) flow through the 5 GPM flowmeter. Set the dial indicator reading to zero.

After valve flow null has been determined close pressure port SOV 2, turn down system pressure regulator, open bypass valve and turn off hydraulic test stand.

STEP 1

With valve at neutral start turning adjusting screw to move the valve spool .01 inch extend into housing. At start of motion record maximum value of friction and then record value of running friction force as adjusting screw is being turned to .01 inch total value spool travel.

STEP 2

Return valve spool to null and repeat Step 1 with motion in the retract direction. Return valve to neutral (zero reading on dial indicator.)

5.2.2 CONTROL VALVE FLOW REACTION FORCE AND FLOW OUTPUT MEASUREMENT WITH 500 PSI ACROSS SINGLE VARIABLE CYLINDER EXTEND ORIFICE 2

Starting with the actuator connected as shown in Figure 4A and with the final Hydraulic Test Stand value settings given in 5.2.1, turn on the test stand pump.

Open pressure port SOV 2, close the bypass valve and turn up the system pressure regulator on the test stand to obtain a supply pressure of 500 psi above return pressure.

STEP 1

To measure flow and valve reaction force position the valve spool in 0.005 inch increments from null to 0.070 inch extend displacement recording flow readings and valve reaction force for each increment in valve position. When flow exceeds 4.0 gal./min. close SOV B and open SOV C to record flow up to 20.0 gal./min. A plot of flow vs spool displacement should fall within the bounds shown in curve 2 of Figure 6 which is taken from curve 2 of Appendix B, page 29.1 of MCDONNELL AIRCRAFT CO. SPEC. CONTROL DWG. 32-69915, Revision B. After final readings return valve to neutral, open SOV B, close SOV C, close pressure port SOV 2 and shutdown hydraulic test stand.

5.2.3 CONTROL VALVE FLOW AND REACTION FORCE MEASUREMENT WITH 500 PSI ACROSS SINGLE VARIABLE CYLINDER RETRACT ORIFICE $\triangle 4$

Starting with the final conditions of the previous test, close SOV A and the return port SOV's 1 & 2 on the test stand. Disconnect the pressure line to P2 on the actuator and connect it to test port C4. Disconnect the flowmeter line from test port 3 and plug T.P.3. Disconnect R 2 from return port 1 on the test stand.

Open SOV A, Return port SOV's 1 & 2 and supply port SOV 2 on the test stand. Start up hydraulic test stand, increase pressure slowly and check for leakage at connections.

Increase supply of pressure to 500 psi and repeat procedure of Step 1 of 5.2.2 measuring flow and reaction forces.

A plot of flow vs spool position should fall within the bounds shown in curve $\triangle 4$ of Figure 6 which is taken from curve $\triangle 4$, appendix B, page 2912 of MCAIR SCD 32-69915 revision B.

5.2.4 FLOW AND VALVE REACTION FORCE MEASUREMENT WITH 1000 PSI & 2000 PSI ACROSS TWO VARIABLE ORIFICES IN SERIES, $\triangle 2$ AND $\triangle 4$

Connect the actuator to the test stand as shown in Figure 4B with a cylinder bypass line, SOV and test gage between the actuator control valve test ports C3 & C4.

Turn on hydraulic test stand and observing normal precautions increase supply pressure to 1000 psi above return pressure with valve at neutral.

STEP 1

Position the valve spool in 0.005 inch increments from neutral to 0.070 inch extend displacement recording flow readings, valve position and bypass line pressure. When flow exceeds 4.0 gal./min. close SOV B and open SOV C. After final reading return valve to null. Close SOV C and open SOV B.

STEP 2

Increase supply pressure to 2000 psi above return pressure and repeat Step 1.

After Step 2 is completed, close pressure port SOV 2, return port SOV 2 and SOV A. Shutdown hydraulic test stand.

5.2.5 FLOW AND VALVE REACTION FORCE MEASUREMENT WITH 1000 PSI AND 2000 PSI ACROSS TWO SETS OF TWO VARIABLE ORIFICES IN SERIES

Connect the actuator to the test stand as shown in Figure 4C with cylinder bypass lines across the test ports. Open pressure port SOV's 1 & 2, return port SOV's

5.2.5 Cont.

1 and 2 and SOV A to flowmeters. Turn hydraulic test stand on and observing normal precautions increase supply pressure to 1000 psi above return pressure with valve at neutral.

STEP 1

Repeat the procedure of Step 1 of 5.2.4, with valve moved in retract direction instead of extend.

STEP 2

Increase supply pressure to 2000 psi above return pressure and repeat Step 1 of 5.2.4, with valve moved in retract direction instead of extend. After Step 2 is completed, close pressure port SOV's 1 and 2, return port SOV's 1 and 2 and SOV A. Shutdown hydraulic test stand.

5.3 FORCE MOTOR/CONTROL VALVE/ACTUATOR ASSEMBLY

The following tests will be conducted on the force motor /control/valve/actuator assembly to determine performance of the control valve module.

5.3.1 CLOSED LOOP FORCE MOTOR/CONTROL VALVE POSITION VS INPUT VOLTS, NO FLOW

Position the actuator in the test fixture as shown in Figure 7. Connect the force motor/control valve module to the breadboard servoelectronics as shown in Figure 3. Attach a dial indicator to the control valve module to measure spool position.

STEP 1

The common input command to the dual servoelectronics will be varied from zero to full valve extend position command, then to full retract command and back to zero in discrete steps with the output position, F.M. current and common input command recorded.

STEP 2

Step 1 will be retreated with only coils 1 and 2 (channel 1) of the force motor connected.

5.3.2 CLOSED LOOP FORCE MOTOR/VALVE POSITION AND FLOW MEASUREMENT WITH 1000 PSI AND 2000 PSI ACROSS THE TWO SETS OF CONTROL ORIFICES IN SERIES

With the actuator in the test fixture and connected to the servoelectronics as in 5.3.1 above, connect the control valve to the 34 GPM Hydraulic Test Stand as

5.3.2 Cont.

shown in Figure 4C. Observing normal precautions start hydraulic test stand and increase supply pressure to 1000 psi above return pressure.

STEP 1

The common input command to the dual servoelectronics will be varied from zero to full valve retract position in 0.005 inch increments. With 1000 psi across the valve, record flow output, F.M. /Valve position, F.M. current and common input command. When flow exceeds 4.0 gal. /min. close SOV B and open SOV C to the 20 gpm flowmeter. After final reading, return F.M. /valve position to neutral. Open SOV B and close SOV C.

STEP 2

Increase supply pressure to 2000 psi above return pressure and repeat Step 1.

After Step 2 is completed, close pressure port SOV 2, return port SOV 2 and SOV A. Shutdown hydraulic test stand.

5.3.3 CLOSED LOOP FORCE MOTOR/CONTROL VALVE FREQUENCY RESPONSE AND THRESHOLD TEST, NO FLOW

With the actuator still connected as in procedure 5.3.2, conduct frequency response and threshold tests using the procedure given in Step 1 through Step 3 of 5.1.6. In Step 4 of 5.1.6 the frequency response and threshold tests will be conducted using only coils 1 and 2 (channel 1) of the force motor.

5.3.4 CLOSED LOOP FORCE MOTOR/CONTROL VALVE FREQUENCY RESPONSE AND THRESHOLD TEST, WITH FLOW AT 1000 PSI & 2000 PSI ACROSS THE TWO SETS OF CONTROL ORIFICES IN SERIES

With the actuator still connected as in procedure 5.3.2, open return port SOV 2, pressure port SOV 2 and SOV A. Turn on hydraulic test stand and increase supply pressure to 1000 psi above return pressure.

STEP 1

Following the basic procedure of 5.1.6 set the frequency analyzer initial frequency at 0.1 Hz and adjust the amplitude to achieve $\pm$ 10% of full force motor/valve stroke. Close return port SOV 2 and make sure SOV C is closed so that flow is through the 5 GPM flowmeter. Record the maximum value of flow as shown on the 5 GPM flowmeter. Open return port SOV 2 and close SOV A. Also close SOV D and SOV E to the test gages on the test port bypass lines. Proceed with the frequency respond test as given in Step 1 of procedure 5.1.6.

5.3.4 Cont.

STEP 2

After completing Step 1, reduce the frequency to 0.1 Hz. Close SOV B, open SOV C to the 20 GPM flowmeter, open SOV A and close return port SOV 2. Increase the supply pressure to 2000 psi above return pressure, and record the maximum value of flow shown on the 20 GPM flowmeter. Open return port SOV 2 and Close SOV A. Proceed with the frequency response test as given in Step 1 of procedure 5.1.6.

STEP 3

After completing Step 2, reduce frequency to 0.1 Hz and increase amplitude to ± 50% of full F.M./Value stroke. Close SOV 2, Open SOV A and record maximum flow. Open SOV 2, close SOV A and proceed with frequency response test as in Step 1 of procedure 5.1.6.

STEP 4

After completing Step 3 reduce frequency to 0.1 Hz and then reduce pressure to 1000 psi above return pressure. Record maximum flow as in Step 3 and proceed with frequency response as in Step 1 of procedure 5.1.6.

STEP 5 THRESHOLD TEST

With the supply pressure at 1000 psi above return, conduct the threshold test as described in Step 3 of procedure 5.1.6.

STEP 6

Increase supply pressure to 2000 psi above return pressure and repeat Step 5.

STEP 7

Repeat Steps 1, 2, 3, 4, 5 and 6 with only Channel 1 (coils 1 and 2), connected to the F.M./control valve module.

After completion of Step 7, close pressure port SOV's 1 and 2. Return port SOV's 1 and 2 and SOVA. Shutdown hydraulic test stand.

5.3.5 AILERON ACTUATOR OUTPUT VELOCITY, OPEN LOOP, VS F.M./CONTROL VALVE POSITION AT 1000, 2000, AND 3000 PSI

Before starting this test, disconnect the control valve test port C_1, C_2 and C_3 C_4 cylinder bypass lines and screw the plugs into the test ports. Open return port SOV's 1 and 2 and supply port SOV's 1 and 2 on the test stand. Observing normal precautions increase pressure to 500 psi with F.M./control valve at neutral.

Using the common input command to the dual servoelectronics position the F.M. /control valve to cause the aileron actuator to drift to full extend position. Set the actuator test fixture dial indicator to zero reading. Connect one channel of strip chart recorder to the demodulated output of one of the actuator cylinder LVDT's. Position the control valve to cause full retact motion of the aileron actuator. Record the dial indicator readings which should be about 2.20 inch full actuator travel. Adjust the strip chart recorder to obtain full scale displacement corresponding to the measured actuator travel.

From previous test data determine the required input command to obtain ± 10%, ± 33%, ± 66& and ± 99% of full Force motor/control valve displacement. Connect one of the F.M. LVDT, demodulated outputs to the strip chart recorder together with the common input command.

STEP 1

Increase the supply pressure to 1000 psi above return pressure with the actuator at full retract position.

Adjust the common input command to +10% extend command and using a switch introduce the +10% command as a step input recording the change in actuator position on the strip chart recorder. Calculate output velocity from the time to travel full stroke and the measured actuator travel. Reverse input command polarity to -10% (retract command) and record retract position change. Repeat above procedure for 33%, 66% and 99% full valve travel command inputs.

STEP 2

Increase supply pressure to 2000 psi above return pressure and Repeat Step 1.

STEP 3

Increase supply pressure to 3000 psi above return pressure and repeat Step 1.

After testing is completed shutdown hydraulic test stand.

5.4 DIRECT DRIVE ACTUATION SYSTEM TESTS

The following tests will be performed on the force motor/control valve/ actuator assembly and breadboard servoelectronics to determine system performance.

5.4.1 CLOSED LOOP POSITION GAIN, TRACKING AND SERVOELECTRONICS GAIN MEASUREMENTS

With the actuator in the test fixture positioned 0.175 inch frum full retract, connect the outputs of the four aileron actuators LVDT's to the breadboard servoelectronics. Measure the AC voltage output of the LVDT's and adjust the probes to obtain the minimum null output. Measure the DC voltage at the output of the demodulators with the input shorted to determine DC offset. Remove the short and measure the DC voltage to determine the total offset which is the sum of LVDT in-phase null voltage and demodulator DC offset. Set the test fixture dial indicator at zero. With a zero command input and essentially zero feedback voltages, ground the inputs to the servoamplifiers and measure the DC null (offset) currents.

With the actuator connected to the hydraulic test stand as in procedure 5.3.5, open return port SOV's 1 and 2 and supply port SOV's 1 and 2 on the test stand. Turn on hydraulic test stand and observing normal precautions increase supply pressure to 3000 psi above return system pressure. With the actuation system now in operation closed loop and with zero common command input observe the test fixture dial indicator to determine if a position null shift has occurred. Record the position null shift value.

Set the dial indicator reading at zero. Vary the common input command from zero to full aileron actuator extend position, then to full retract position and back to zero recording the dial indicator readings at full extend, retract and null positions. Full extend position should be 2.025 $\pm$ .010 inch and full retract should be 0.173 $\pm$ .010 inch according to Appendix A, Sheet 28, Note 1 of MCAIR SCD 32-69915 Revision B.

STEP 1

The common input command to the servoelectronics will be varied from zero to full aileron actuator extend position, then to full retract command and back to zero in discrete steps equivalent to 0.1 inch actuator position. At each discrete step the input command, LVDT AC voltages, demodulated DC LVDT voltages, force motor currents and dial indicator position will be recorded.

STEP 2

Repeat Step 1 with only coils 1 and 2 of the Force Motor (Channel 1 electronics) connected.

STEP 3

Connect a set of four LVDT's to the actuator stick command input buffer amplifiers of the servoelectronics and repeat the procedure given in Step 1.

Step 3 Cont.

Measure the LVDT AC output voltages and demodulated LVDT DC output voltages in addition to the measurements taken in Step 1, as the probes of the stick input LVDT's are varied to cause the aileron actuator to move through a full extend/retract cycle.

STEP 4

Repeat Step 3 with only coils 1 and 2 of the force motor (channel 1 electronics) connected.

5.4.2 FAULT DETECT LEVELS AND FAILURE TRANSIENT TESTS

STEP 1

With the actuator connected to the servoelectronics and test stand the same as in Step 1 of procedure 5.4.1, introduce a command input to one of the actuator inputs with the other command inputs at zero. As the input command is increased record the input command, actuator output motion and force motor currents on a strip chart recorder. Record the value of input command required to cause the failure detect circuit to trip and disconnect the coils in that channel. Record the null shift in actuator position, if any, shown on the dial indicator after the failure has caused disconnect of one channel.

STEP 2

Reduce the failure command to zero, reset the failure detect circuits and repeat Step 1 for a failure command in the other channel.

STEP 3

Reduce the failure command to zero, reset the failure detect circuits and inhibit the failure detect circuit from operating. Increase the failure command to one input, as in Step 1, until the servoamplifier current to the single coil saturates. Record the maximum position shift. Then introduce a variable command to the other three (3) inputs which cyles the actuator over the full travel to demonstrate performance with an input failure and a failure to disconnect.

STEP 4

After completing step 3, remove the input commands and the fail detect circuit inhibit.

Introduce a sinusoidal command to both inputs of the two channels, recording input command, output position and force motor currents. Ground or open various input or feedback paths and determine the failure transients. Also determine the effects of power supply failures and open or shortened LVDT outputs.

5.4.3 CLOSED LOOP ACTUATOR FREQUENCY RESPONSE AND THRESHOLD TEST

With the actuator connected to the servoelectronics and test stand, connect the output of the EMR frequency analyzer to the common command input and the output of the channel 1 actuator feedback path LVDT demodulator to the input of the EMR analyzer.

STEP 1

The initial frequency will be set at 0.1 Hz and the amplitude adjusted to achieve a total peak to peak actuator motion of 0.22 inch which is 10% of a 2.2 inch travel. The sinusoidal amplitude is then 0.11 inch which is 10% of a $\pm$1.1 inch stroke from actuator cylinder midposition. The frequency will be changed in discrete steps from 0.1 Hz to 15 Hz or that frequency which results in 180° phase shift. The actuator output amplitude and phase shift as a function of frequency will be recorded. The input command, actuator feedback voltage, force motor position feedback voltage and coil voltage proportional to current will be recorded on a multi channel strip chart recorder.

STEP 2

Repeat Step 1 with only channel 1 (coils 1 & 2) of the force motor connected.

STEP 3

Repeat Step 2 for an amplitude equivalent to 5% of a $\pm$1.1 inch stroke (0.11 inch peak to peak.)

STEP 4

Repeat Step 1 for an amplitude equivalent to 5% of a $\pm$1.1 inch stroke.

STEP 5 THRESHOLD TEST

Set the frequency at 0.159 Hz (1 radian/sec) and reduce the input command until the actuator output motion stops. Record this input amplitude.

STEP 6

Repeat Step 5 with only channel 1 (coil 1 and 2) connected to the force motor.

5.4.4 OPERATION ON DUAL HYDRAULIC SUPPLIES WITH ONE AT AN OVER TEMPERATURE CONDITION

With the actuator in the test fixture and connected to the servoelectronics, connect the P_2, R_2 aileron actuator ports to the 34 GPM hydraulic test stand using a cylinder bypass line between test ports C_3, C_4 as shown in Figure 4B. Connect the actuator P_1, R_1 ports to the Greer Hydraulic Test Stand in a similar manner to that shown for the P_1, R_1 system in Figure 4C. Connect a cylinder bypass line between the C_1, C_2 test ports. Connect Thermocouples in the actuator R_1 and $R2$, return lines to measure oil temperature. The test will be conducted with the force motors position loop closed but the actuator position loop will be open. Disconnect the actuator position feedback to the servoelectronics.

The basic measurement technique employed in this test to determine if the control valve has any tendency to stick or bind as the temperature of the oil in one system is increased, will be to record the common input command and force motor/valve spool position on an X-Y recorder and compare the hysteresis plots at different oil temperatures. Force motor currents and position will also be recorded on a strip chart recorder. Return line (R_1, R_2) actuator outlet oil temperatures will be recorded on a temperature recorder.

With the actuator connected to the two test stands, increase the supply pressure to 1000 psi above return pressure. Connect the common command input and the #1 channel force motor position output to the X-Y recorder. Vary the common input to cycle the valve through a full extend/retract cycle and calibrate the X-Y recorder and strip chart recorder. During calibration record flow output and compare with data taken in procedures 5.2.5 and 5.3.2.

STEP 1

Connect a sinusoidal signal generator to the common input and set the frequency at 0.1 Hz. Adjust the amplitude to achieve a full valve stroke cycle and record the output position to input command, currents, and temperature data. The initial oil temperature of both hydraulic test stands should be $80^\circ \pm 10^\circ$ F. After recording the hysteresis loop, reduce the signal generator amplitude to maintain the 34 GPM Hydraulic Test Stand R_2 return line oil temperature at 80°-90° F.

STEP 2

Increase the oil temperature of the Greer hydraulic test stand and record the hysteresis loop data per Step 1 at oil temperature differences of $20^\circ \pm 5^\circ$ F, $65^\circ \pm 5^\circ$ F and $100^\circ \pm 5^\circ$ F. After completion of last test point decrease temperature of Greer test stand. When temperature returns to normal, shutdown both hydraulic test stands.

5.4.5 STATIC STIFFNESS TEST

Position the actuator in the Vibration/Stiffness/Endurance test fixture as shown in Figure 8 and connect both P_1, P_2 actuator ports to the same 3000 psi hydraulic system. Connect the test fixture loading cylinder to a variable pressure source as shown in Figure 8. Set up dial indicators as shown to measure actuator cylinder motion with respect to the fixed rod end and rod end motion with respect to the test fixture. Connect the actuator to the breadboard servoelectronics.

Disconnect the psiton rod end of the loading cylinder from the test fixture. Turn on the variable pressure source, and determine the extend and retract pressures required to overcome friction in the loading cylinder.

With the breadboard servoelectronics on, turn on the aileron actuator hydraulic pressure source, adjust pressure to 3000 psi, and position the actuator at mid-travel. Connect the loading cylinder to the test fixture. Set the dial indicator readings on the fixture at zero.

STEP 1

With the variable pressure source connected to the extend side of the loading cylinder, slowly increase the pressure in increments recording the actuator LVDT output position, load cylinder pressure and dial indicator readings. When a load pressure of 3000 psi is reached, start decreasing pressure back to zero in finite increments recording the same data. Reverse the loading cylinder connections to cause the load cylinder to retract and repeat the procedure given above.

STEP 2

Repeat Step 1 with only channel 1 (coils 1 and 2) of the force motor connected.

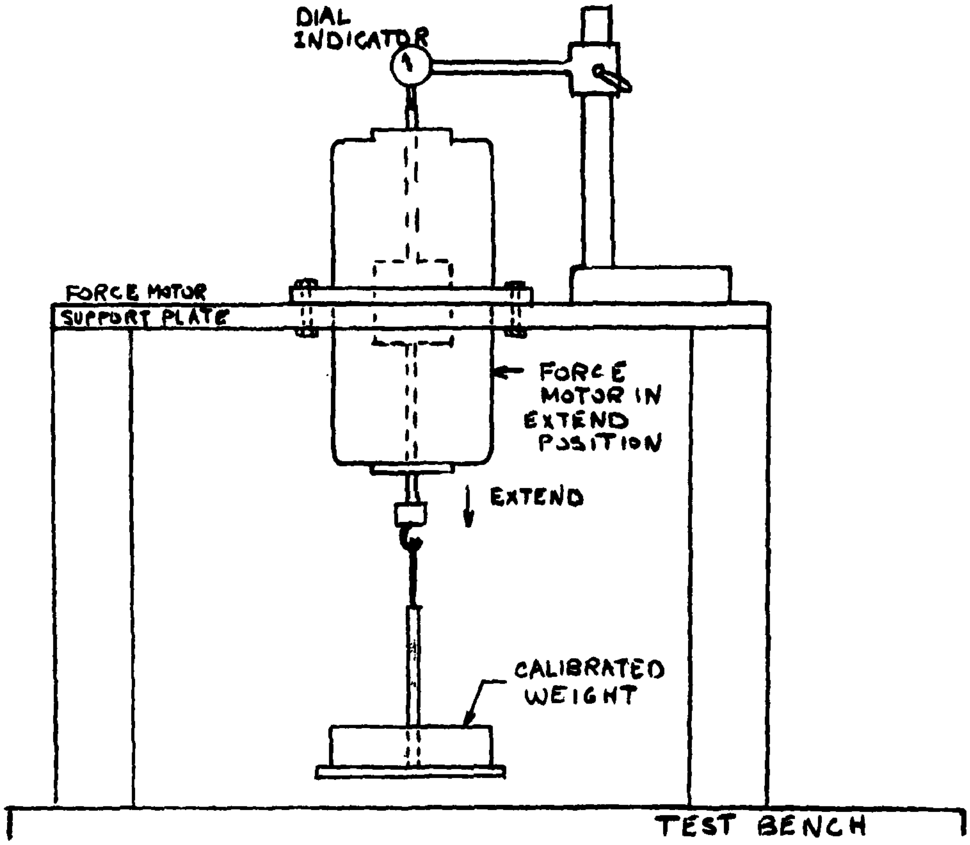
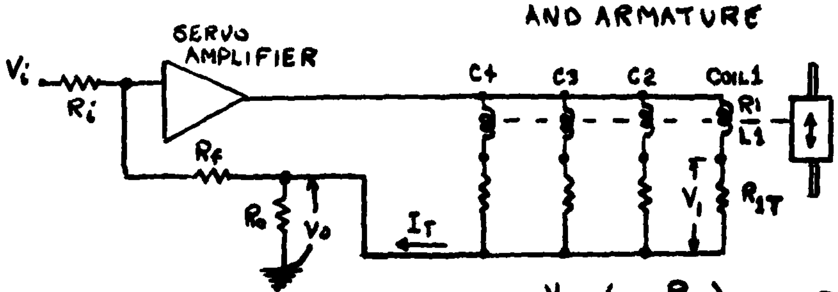


FIGURE 1 CENTERING SPRING FORCE, FORCE MOTOR GAIN AND FORCE MOTOR OUTPUT TEST SET UP



$R_o \ll R_1$ = COIL RESISTANCE
R_{1T} = TEST RESISTOR $\ll R_1$

$I_T = \frac{V_o}{R_o}\left(1 + \frac{R_o}{R_f}\right)$ = TOTAL CURRENT
$I_1 = V_1/R_{1T}$ = #1 COIL CURRENT

FIGURE 2 FORCE MOTOR POSITION VS CURRENT, HYSTERESIS AND FORCE MOTOR OUTPUT TEST CIRCUIT SCHEMATIC

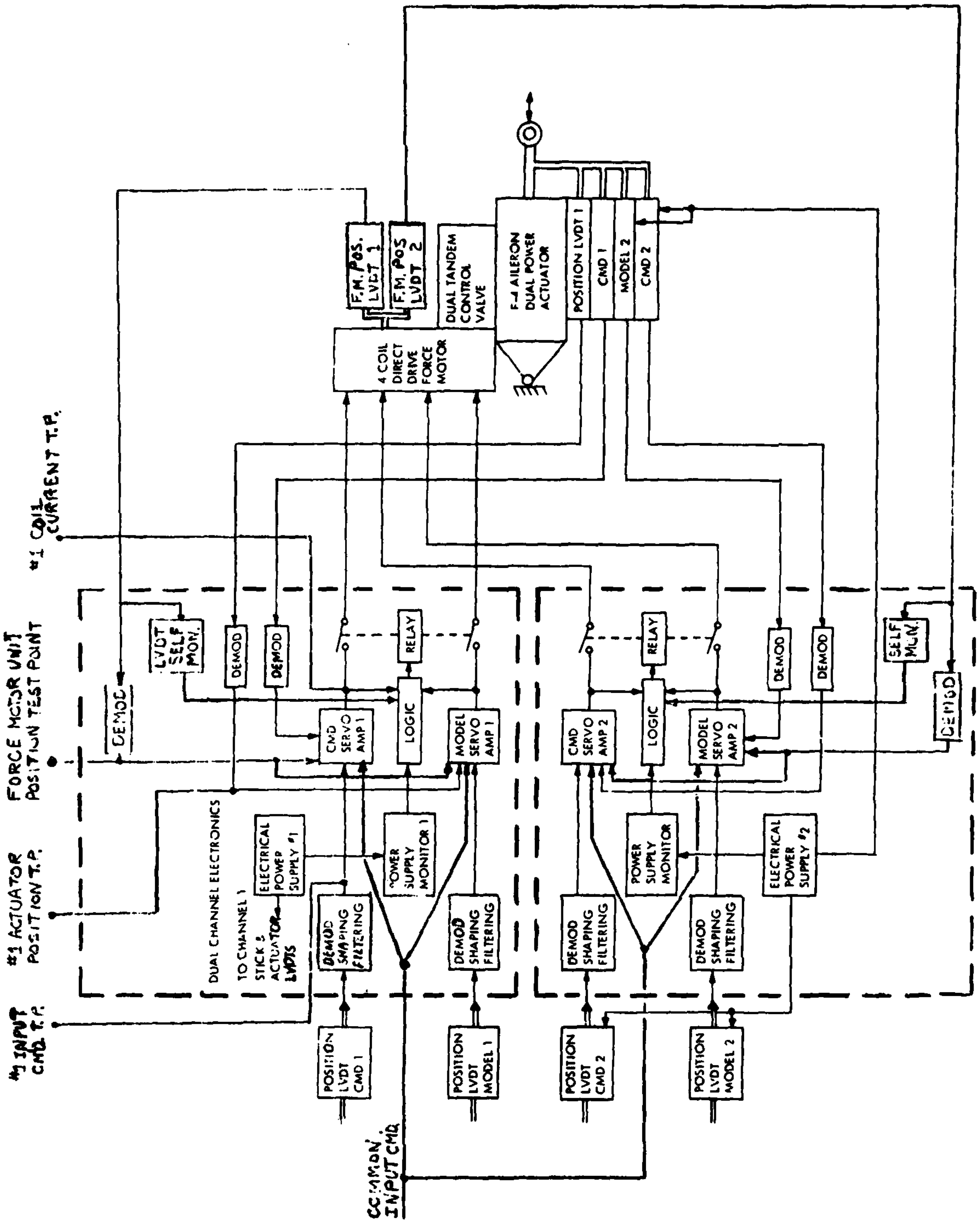


Figure 3 BREADBOARD DIRECT DRIVE ACTUATOR DUAL CONTROL ELECTRONICS

FIGURE 4A TEST SET UP FOR SINGLE CONTROL VALVE ORIFICE FLOW AND REACTION FORCE MEASUREMENT

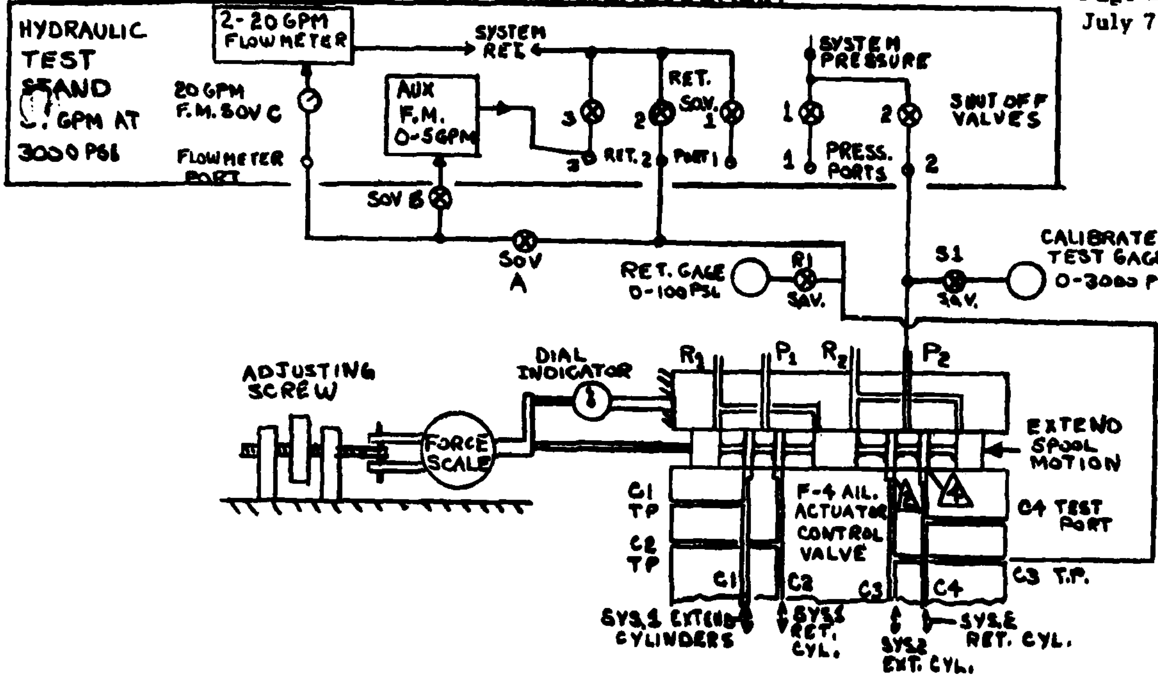


FIGURE 4B TEST SET UP FOR TWO CONTROL ORIFICES IN SERIES FLOW AND REACTION FORCE MEASUREMENT

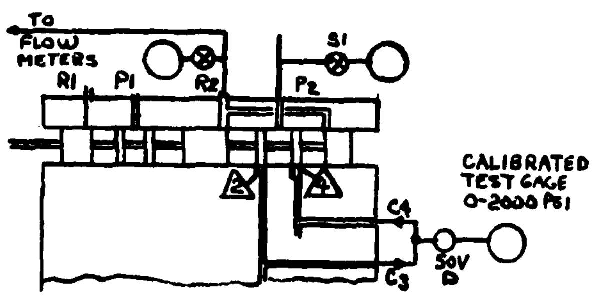


FIGURE 4C TEST SET UP FOR TWO SETS OF TWO CONTROL ORIFICES IN SERIES FLOW AND REACTION FORCE MEASUREMENT

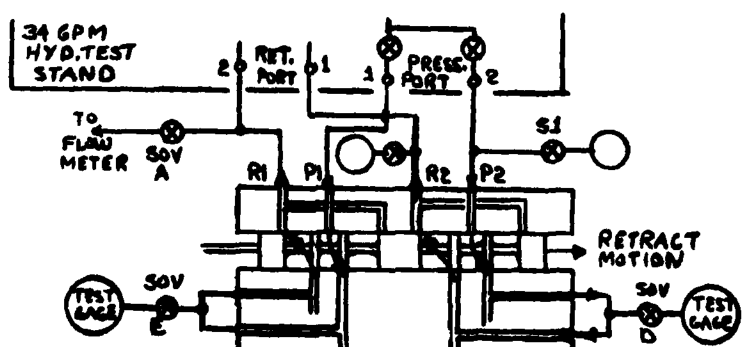


FIGURE 4 TEST SET UP FOR VALVE REACTION FORCE AND FLOW MEASUREMENT

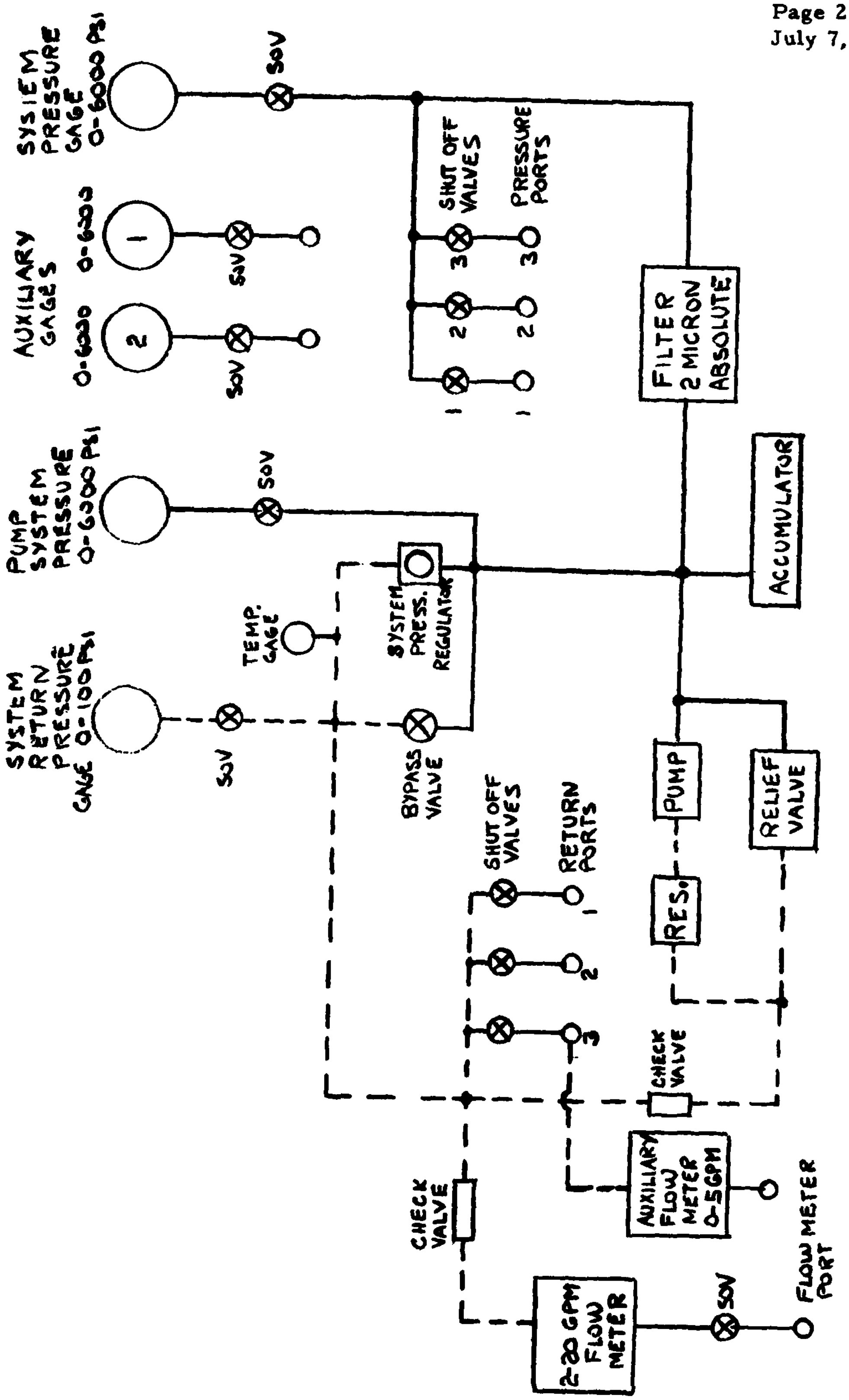


FIGURE 5 SCHEMATIC, HYDRAULIC TEST STAND 34 GPM AT 3000 PSI

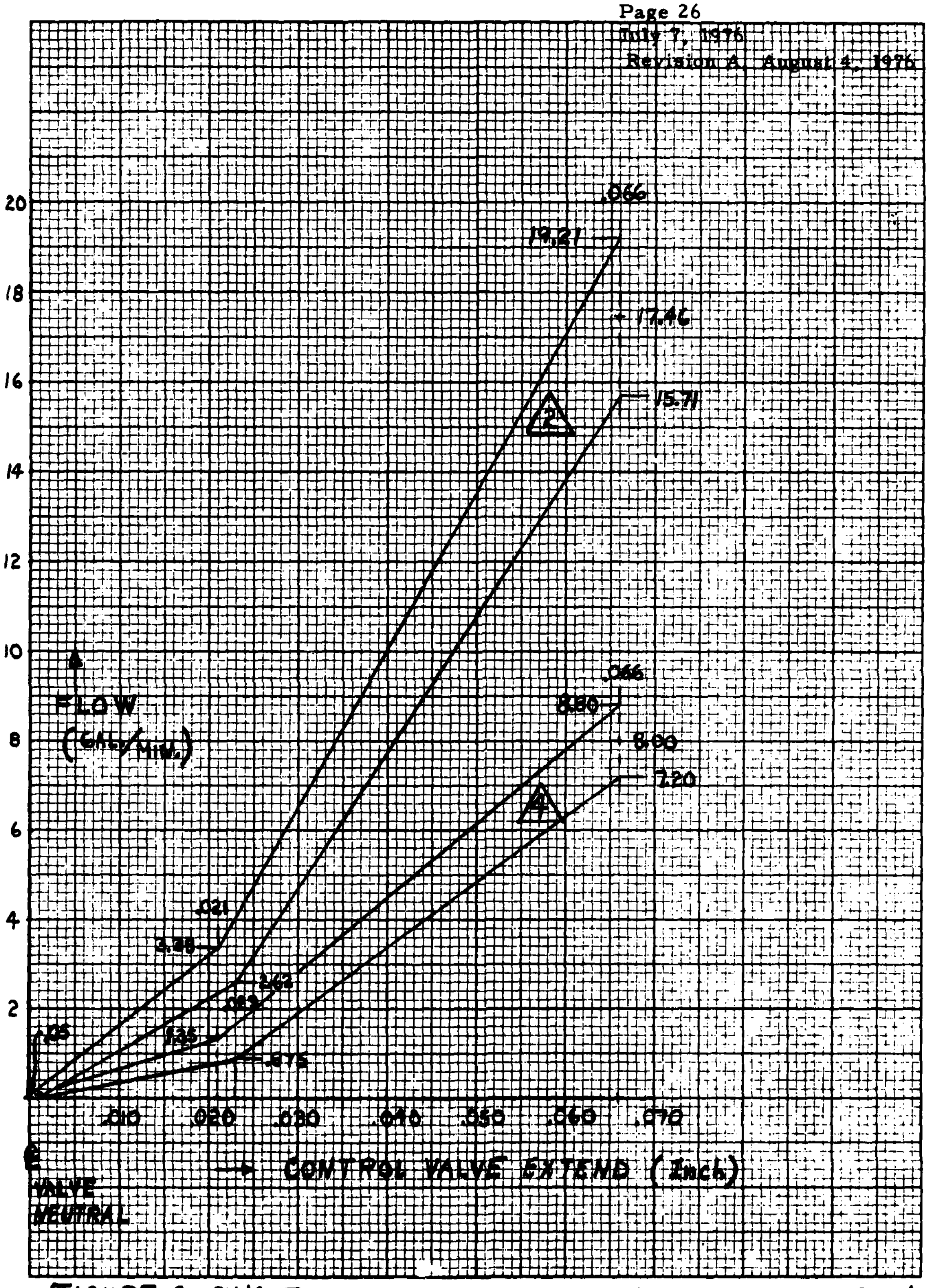


FIGURE 6 SINGLE CONTROL ORIFICE FLOW VS SPOOL POSITION

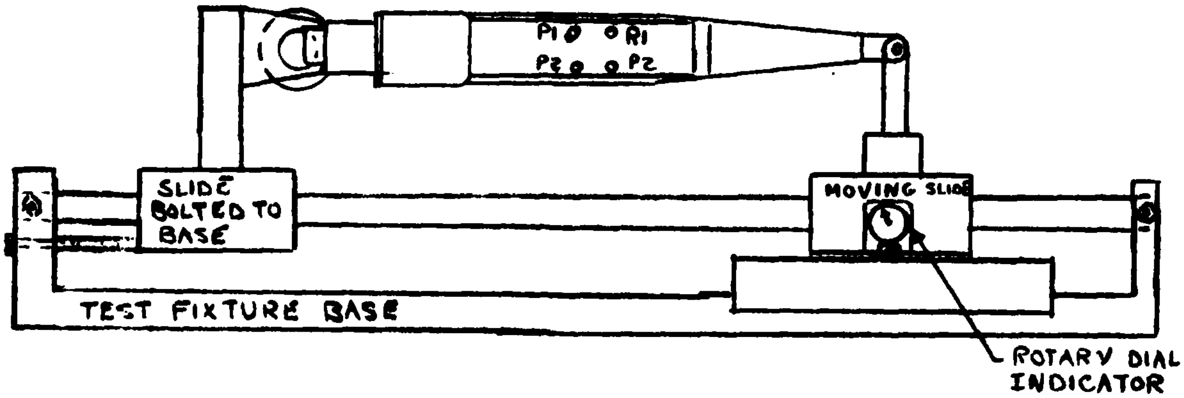


FIGURE 7 AILERON ACTUATOR NO LOAD TEST FIXTURE
(MODIFIED SIMPLEX ACTUATOR TEST FIXTURE)

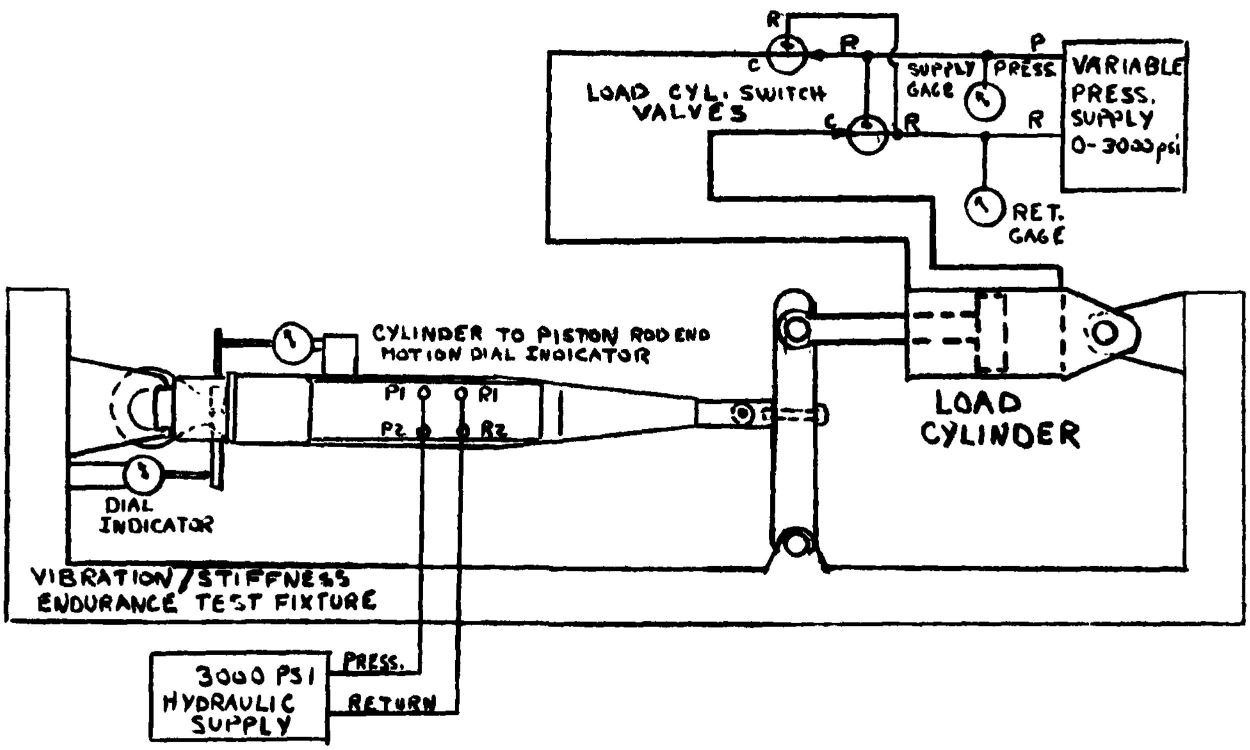


FIGURE 8 STATIC STIFFNESS TEST SET UP

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